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SOIL VARIABLES FOR USE IN ECONOMIC ANALYSIS

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As a preliminary step in evaluating the economic benefits of soil conservation practices, it has been necessary to quantify physical soil productivity in terms of a minimum number of variables. With this objective in view, this paper reports the preliminary results of a graphical analysis of functional relations between certain soil characteristics and yields of Yellow Newtown apples in the lower Pajaro Valley in Santa Cruz County, California. It has been concluded that the percentage by weight of surface soil particles 5 microns or less in diameter, or the corresponding ***moisture equivalent,*** may be used as a fairly adequate representation of the more important surface soil characteristics within the research area. Factor A of the Storie soil-rating index similarly may be used to represent approximately the soil profile characteristics. Variations in these two measures and in tree age accounted for about 44 per cent of the variations in yields.

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DAVID WEEKS[2] and J. HERBERT SNYDER[3]

PRECISE quantitative measurement of the physical productivity of different classes of land in terms of soil properties and other variables has long been recognized as a prerequisite to the analysis of their economic productivity. Thus, the basic concept of physical productivity as a function of the soil, climate, crop, time, and management is not new (Jenny, 1941, p. 245). The research reported here is an effort to express this concept empirically. The large number of variables and other physical and economic complexities heretofore have prevented satisfactory accomplishment of this objective.

As a basis for the evaluation of direct economic benefits from soil conservation practices in the lower Pajaro Valley of Santa Cruz County, California, relations were observed between Yellow Newtown apple yield, age of orchard, and certain soil characteristics which were selected, tested, and found to be approximately representative of the entire physical soil body and capable of quantitative expression. Field work on the study was conducted between 1947 and 1953. Climate was considered uniform throughout the research area although differences in precipitation and temperature associated with differences in elevation probably account for some of the unexplained differences in yield. The crop was held constant, as previously indicated, by observing the average yield of a single crop—Yellow Newtown apples. Time was held constant by using average yields over a period of six years. Management was held constant at the average of each major management practice by soil profile-texture group and subsequently was adjusted to the general average for each major management practice. Thus, a point of departure was provided by this research for observing in later research the significance of variation of the different management practices.

Although the variables and the relations among them are expressed only in physical terms, they were designed by economists, aided by soil scientists, for use in economic analysis. Because of the possibilities of their application to a wide variety of purposes, the methods of this study are presented here

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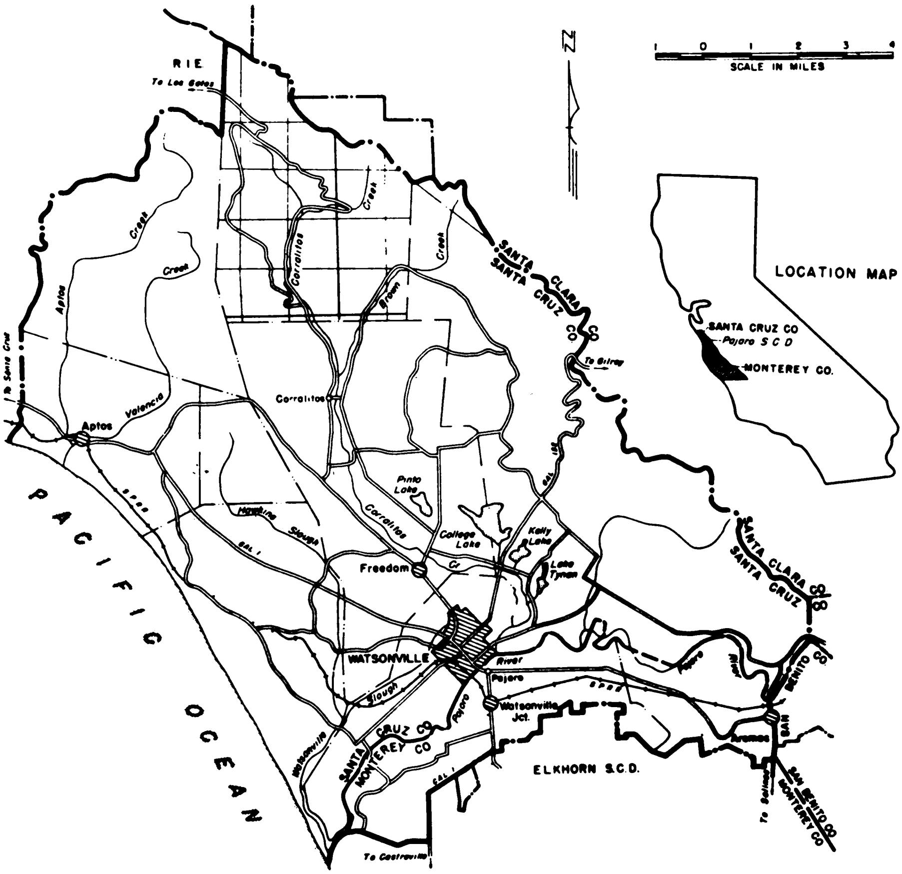


Fig. 1. Pajaro Soil Conservation District showing location of the research area.

independently of the evaluation of soil conservation practices for which they were designed.

The research is comprised of two parts: (1) the selection and testing of the soils, orchard age, and yield variables and (2) the approximate mathematical expression of the functional relations existing among these variables.

THE RESEARCH AREA

The research area lies within the lower Pajaro Valley and is that part of the Pajaro Soil Conservation District lying within the boundaries of Santa Cruz County, California (fig. 1). A large part of the 32,500 acres of Santa Cruz County cropland lies within this district.

The development of agriculture in Santa Cruz County began about a century ago. Apples, still the most important single crop, were introduced in 1852 reaching their maximum expansion of about 12,000 acres in 1930.

During the 15-year period ending in 1955, however, the bearing acreage of apple orchards declined nearly 12 per cent while the bearing acreage of all orchard and vineyard crops of the county declined 25 per cent. These orchards and vineyards were replaced by vegetables, berry crops, and about 700 acres of forest and grass that had gone out of cultivation altogether.

Physical Characteristics

The climate of the lower Pajaro Valley is characteristically Mediterranean, with a dry season extending from May to October and a wet season from October to May, although typically one half of the annual rainfall occurs during December, January, and February. Mean annual rainfall in the research area varies from about 28 inches near Watsonville to nearly 45 inches in the cultivated hilly upland. Killing frosts may occur from November to March, but the mean monthly temperature varies only from about 50° F in the winter months to 62° in the summer months. Morning and evenings fogs—of frequent occurrence in the Pajaro Valley—benefit the farmer by retarding the evaporation of soil moisture.

The topography of the research area varies from alluvial fan and stream bottomland to hilly or semimountainous upland. Most of the farms studied in this project were on lands of sufficient slope to constitute soil conservation problem farmland.

Five land types have been defined in Santa Cruz by Storie as follows: "A, the alluvial fan and flood plains; B, the flatter basin-like land; C, the low terrace land; D, the high terrace land; and E, the upland or mountainous land" (Storie, 1940). All of these broader types and their many variants are represented in the research area. The wide variation in the soils of the area have made it possible to observe crop growth and yields—particularly of apples, the plant indicator of this research—under extremes of soil conditions ranging from the highly productive alluvial soils of the Pajaro River flood plain to the clay pan soils having restricted root and water penetration on the higher terraces.

Detailed consideration will be given to the specific soils encountered in the conduct of the research in later sections of this discussion.

SELECTION AND TESTING OF THE SOILS VARIABLES

Existing soil surveys do not provide descriptions of soil properties readily adaptable to the determination of functional relations between the soil and its productivity.

Two kinds of soil surveys were available for the research area: the Federal State Cooperative Soil Survey of the Santa Cruz area, made by the former United States Bureau of Plant Industry, Soils, and Agricultural Engineering (Storie, *et al.*, 1944) and the Soil Conservation Survey of the United States Soil Conservation Service (United States Soil Conservation Service, 1951, 1952; Wohletz, 1948). In addition to these surveys, a special soil map was made by the Soil Conservation Service of each farm in the research sample. Soils classified by either of the above surveys are designated by nonquantitative descriptive names, codes, or class numbers.

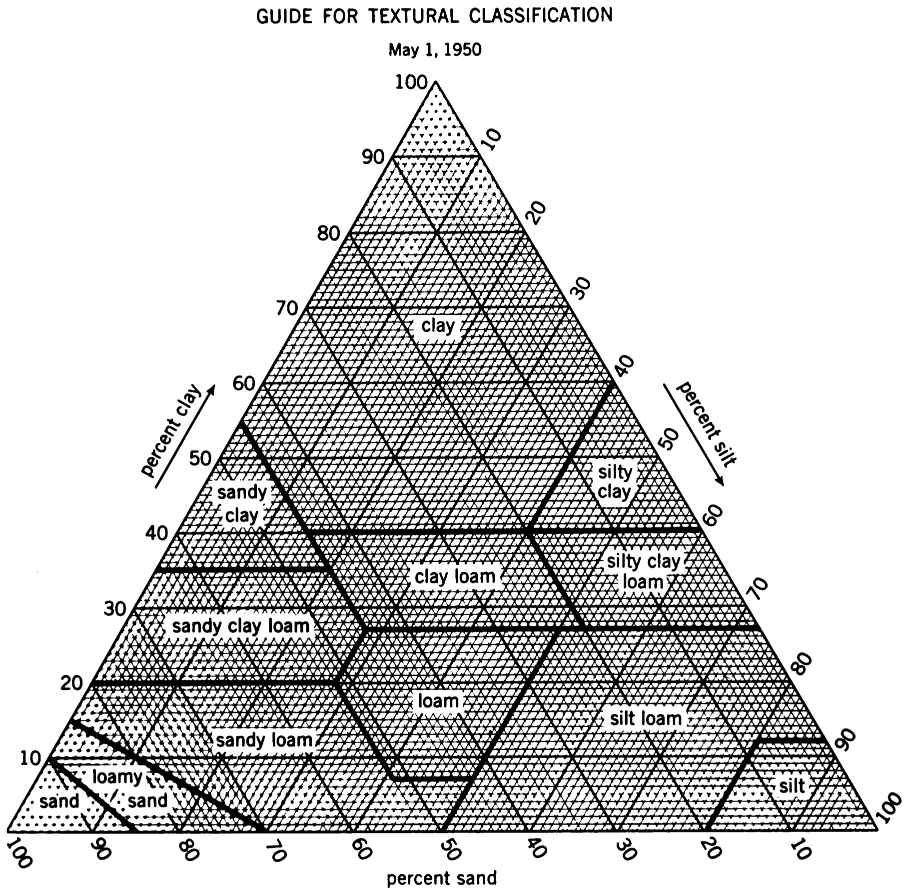


Fig. 2. Soil textural classes and their composition (United States Department of Agriculture, 1951).

Importance of Simplification and Quantification

If soil characteristics are to be correlated with yields, it is highly important that soil properties be given quantitative expression. Also of great importance would be a reduced number of critical measures that would quantitatively tie the different soil classification categories together in a continuous mathematical relation. Such a system would characterize the soil as a physical medium, the productivity of any variant of which may be expressed in terms of the yields of a given plant growing under given conditions of management.

Complex Textural Designations of the Soil Survey. In the soil survey (United States Department of Agriculture, 1951), it is true, the surface *textural class* is given in quantitative terms, that is, in terms of percentages of several particle diameter classes grouped in various combinations. This

TABLE 1
UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL TEXTURAL CLASS NAMES AND THEIR DEFINITIONS
Expressed as percentage ranges of various soil separates

Textural class	Proportions of the soil texture separates		
	Sand	Silt	Clay
Sands	85 or more	Percentage silt plus 1½ times percentage clay shall not exceed 15	
Loamy sands			
Upper limit	85 to 90	Percentage silt plus 1½ times percentage clay not less than 15	
Lower limit	70 to 85	Percentage silt plus 2 times percentage clay does not exceed 30	
Sandy loams	52 or more *or* Between 43 and 52	Percentage silt plus 2 times percentage clay exceeds 30 and 20 per cent clay or less *or* Less than 7 per cent clay, less than 50 per cent silt	
Loam	Less than 52	28 to 50	7 to 27
Silt loam	....	50 or more *or* 50 to 80	12 to 27 *or* Less than 12
Silt	....	80 or more	Less than 12
Sandy clay loam	45 or more	Less than 28	20 to 35
Clay loam	20 to 45	....	27 to 40
Silty clay loam	Less than 20	....	27 to 40
Sandy clay	45 or more	....	35 or more
Silty clay	....	40 or more	40 or more
Clay	Less than 45	Less than 40	40 or more

combining of diameter classes, however, is not consistent from one textural class to another. The result is the highly complex and numerous class designations shown in table 1 and figure 2. Furthermore, the many subclasses not shown in table 1 extend the list to a total of more than 20 textural classes. It would be impossible to select a quantitative texture variable from this array of textural classes that could be used in a correlation with a large number of other variables.

Qualitative Designations of the Soil Profile. Furthermore, it is the qualitative consideration of profile characteristics that results in the designation of a given *soil type* within a given *soil series,* and this designation has little or no quantitative relation to any other soil type of another series.

Limitations of the Soil Conservation Survey. Similarly, in the Soil Conservation Survey, although many of the soil properties are measured and expressed quantitatively, qualitative considerations determine the soil properties to be included in the unit area code.

Significance of the Limitations of Available Soil Surveys. The determination of significant differences in apple yields on only two soils—designated in nonquantitative terms—would require numerous observations for each class of land and for each farming practice. Soils and farming practices are so variable in the area under study that such methods of measurement were found to be prohibitive in terms of numbers of observations, cost, and time required for the sampling and analysis of the numerous categories. Attempts to use these expressions of soil properties in their recorded form proved futile. The establishment of a quantitative relation between categories of a classification and soil properties greatly reduced the number of observations needed.

Consideration of the Use of Soil-Productivity Indexes as Soils Variables

Available soil ratings or productivity indexes were examined to determine their suitability for use as variables representing soil characteristics in correlation analysis, crop yield being the dependent variable.

Kinds of Productivity Ratings. Productivity ratings differ from one another in terms of the kind of reasoning and procedure employed in constructing them and the numbers and kinds of crops serving as a base. The characteristics of some of the more important types are as follows:

1. Soils may be ranked in order of the magnitude of estimated or observed powers to produce a given crop.
2. A soil may be described by a productivity index constructed on the basis of observed or estimated yields of a given crop. Many experiment stations and the former United States Bureau of Plant Industry have constructed indexes of this type (United States National Resources Planning Board, 1941).
3. Ratings may be made of soils in terms of their ability to produce a number of crops. Ratings of this type may be divided into two subgroups according to the kind of reasoning and method of procedure used in making the rating.
   a. On the one hand, the average productivity of a given soil type is measured by the observed or estimated yields of a definite group of crops (United States National Resources Planning Board, 1941).
   b. On the other hand, the productivity index may be a general expression of the productivity of a soil in terms of a less precisely stated number of crops. By observation of the properties of a soil, for example, the degree to which it presents conditions favorable for the extension and development of plant roots, its depth, perviousness, water-retaining capacity, etc., its general suitability for crops and productivity is judged. Thus, a line of reasoning proceeds from the known facts concerning the given soil and the general principles of

plant growth and requirements of growth to the judgment rating given to the soil.

The Storie Index, which is in class 3b, is a judgment of the degree of the ability of the soil to produce a wide range of crops. A description of this index is important at this point because a further development of one of the four "factors" of this index has been used in a phase of the procedure described below.

Percentage values are assigned to the characteristics of the soil itself, including the soil profile (factor A); the texture of the surface soil (factor B); the slope (factor C); and conditions of the soil exclusive of profile, surface texture, and slope—for example, drainage, alkali content, nutrient level, erosion, and microrelief (factor X). The most favorable or ideal conditions with respect to each factor are rated at 100 per cent. The percentage values or ratings for the four factors are then multiplied, the result being the Storie Index rating of the soil. (Storie, 1948.)

The Storie Index serves an important practical need. However, it is subject to some of the limitations outlined below.

Limitations of Productivity Ratings. The various types of soil-rating indexes serve approximately the needs of broad and general studies where precision is not essential. But in some types of farm-organization analysis and particularly in the measurement of the economic effectiveness of different farming practices in conserving the soil, rough measures of soil productivity may introduce errors greater than the critical differences being measured.

Ranking soils does not give a precise quantitative basis of comparison. Both the ranking method and the index based upon the yield of a given crop give ratings that may be reversed when applied to a different crop. The index based upon the yield of a given crop has definite applications, however.

Limitations of productivity ratings for the purposes of the type of research herein reported may be summarized as follows:

1. There is confusion between evaluations of productivity that are purely physical and those that are economic.
   a. Productivity ratings are useful and reliable only after the relation between productivity rating, on the one hand, and yields, net returns, land value, or proved degree of success of a given land use, on the other, has been established.
   b. Management practices (other factor inputs) are as important as soils in producing yields, and differences in yield may measure the productivity of these other factors in confusion with the productivity of the soil. Management practices are highly variable. It is difficult—sometimes impractical and illogical—to measure yields under conditions of equal management.
2. Relative productivities of soils based on yields of one or more specific crops are dependent upon the particular plant or plants used in their measurement. Relative productivity, therefore, is a shifting, not a constant, measure.
3. Mathematical precision and logic implied by equations used in calculating productivity indexes (particularly those of class 3b) do not exist. Such equations usually have been adopted as a practical expedient in systematizing procedures of rating soils and are not the result of reduc-

ing statistical data to mathematical form. True functional relations—where they exist—between soil characteristics on the one hand and plant growth on the other, therefore, are not expressed by these equations.

After considering the above limitations of productivity ratings, it has been concluded that no index of physical productivity of the soil among the types described above can be used as a single variable representing soil properties in a multiple variable correlation problem in which narrow margins of difference are to be measured.

Selecting the Soil Texture Variable

After much statistical experimentation, *the percentage, by weight in the surface soil, of particles 5 microns in diameter or less* has been selected as the soil texture variable. As an alternative to this percentage, the *moisture equivalent* of the surface soil may be used interchangeably.

The selection of this *soil texture variable* as one of two representing the soil has been based upon two sets of considerations: (1) the probable precision with which soil texture can be described by this single quantitative variable and (2) the extent to which soil texture can be depended upon to represent the other physical properties of the soil.

Precision of Soil Texture Description. Traditional textural classes are not precisely described by the soil texture variable selected. However, there is a clear sequence from coarse textural classes to fine, and there is a broad texture class segregation as the percentage of particles having diameters of 5 microns and less increases. This sequence can be observed in table 2, columns 4 and 13. This table presents a mechanical analysis of 29 surface soil samples in the research area. It is of interest to note that the sands, sandy loams, and clays, respectively, are segregated in order of increasing percentages of the particles having small diameters but that loams and sandy clay loams are not differentiated by the array according to diameter size. Such differentiation may not be important, however, with respect to soil productivity. Indeed, the single texture variable selected may have even greater significance than have the traditional categories in indicating productivity. This significance is apparent when the relation of soil texture to other soil properties is given consideration.

The Texture Variable as a Representation of Other Soil Properties. Since the texture of the soil is related to productivity primarily through (1) the retention of moisture available for use by plants and (2) the manufacture and storage of nutrients, it is logical to assume that soil texture can be used to represent, approximately, these two important soil functions, related soil properties, and their many complex interrelations. This assumption is supported by an analysis of 203 soil samples taken from 81 sample sites in the research area.

Because soils in the field are not normally saturated for an appreciable period of time and because interest usually centers on soil moisture conditions between field capacity or moisture equivalent and permanent wilting percentages, this analysis was oriented toward moisture retention of soils and not moisture saturation. Thus, a measure of porosity has not been considered necessary.

Available moisture-holding capacity is a function of moisture equivalent (ME), permanent wilting percentage (PWP), percentage of stone-free soil, soil density, and soil depth (*d*) (Briggs and McLane, 1907). The available moisture function has been expressed as follows:

$$\text{Available moisture} = (\text{ME} - \text{PWP})\begin{bmatrix}\text{per cent of} \\ \text{stone-free soil}\end{bmatrix}\begin{bmatrix}\text{apparent} \\ \text{density}\end{bmatrix}\begin{bmatrix}\text{soil depth} \\ \text{in inches}\end{bmatrix}$$

The moisture equivalent of a soil is that amount of water expressed as a per cent (by weight) of oven-dry soil remaining in a previously saturated soil after it has been subjected to a force of 1,000 times that of gravity for 30 minutes (Bodman, 1938, 1941). Between moisture equivalent values of about 10 per cent and 30 per cent, the moisture equivalent is approximately equal to the normal field capacity (Piper, 1933).

Permanent wilting percentage[4] is that moisture content expressed as a percentage at which plants will wilt and will not recover unless water is added to the soil. Dwarf sunflowers were used as a test plant for permanent wilting-point determinations on 25 samples.

Correlations between the moisture equivalent and permanent wilting percentages have been important considerations in selecting and testing the soil texture variable as a representative of other soil properties. These correlations have made possible the simplification of the available moisture function, reaffirmation of the important relation observed by others between soil texture and moisture retention, and most important of all, a demonstration of the fact that the particular particle-diameter fraction, 5 microns and less, has a greater significance with respect to moisture retention than any other diameter class represented in the mechanical analysis available for the research area.

Simplification of the available moisture function has been accomplished by (1) expressing the permanent wilting percentage in terms of the moisture equivalent percentage, (2) expressing moisture equivalent in terms of the soil texture variable, and (3) eliminating the percentage of small amounts of stone as an important factor.

The permanent wilting percentage as observed in the research area is highly correlated with moisture equivalent. The regression equation expressing this relation is:

$$\text{PWP} = 0.5591 + 0.3976\text{ME} \tag{1}$$

The coefficient of determination, adjusted for sample size, is 0.9229. The high correlation between these variables indicates that within the universe of these observations the moisture equivalent is a reliable indicator of the permanent wilting percentage. On the other hand, Hendrickson and Veihmeyer (1945) state:

> We believe that permanent wilting percentages obtained directly in the field or in the laboratory are more satisfactory than those obtained by indirect methods. Calculation of

[4] Veihmeyer, F. J. Method of determining the permanent wilting percentage of soils. October 9, 1941. (Typewritten manuscript.)

TABLE 2

MECHANICAL ANALYSIS AND MOISTURE EQUIVALENT OF 29 SURFACE SOIL SAMPLES, SANTA CRUZ COUNTY, CALIFORNIA

Sample number	Soil series	S. C. S. mapping symbol	Surface texture from 1950 triangle	Per cent of soil by weight in each particle size group expressed in microns (μ)									Moisture equivalent per cent
				Total	Sand	Silt			Clay			5 and $< 5\mu$	
					$2000>50\mu$	$50>5\mu$	$5>2\mu$	$50>2\mu$	$2>1\mu$	$1–0\mu$	$<2\mu$		
1	2	3	4	5	6	7	8	9	10	11	12	13	14
14-1A	Corralitos	1C	Sand	100.3	89.4	4.3	1.0	5.3	0.9	4.7	5.6	6.6	6.43
37-1A	Corralitos	1C1	Sand	100.1	88.2	5.1	1.4	6.5	0.6	4.8	5.4	6.8	7.60
36-1A	San Andreas	(5)C	Loamy sand	99.7	81.7	6.8	3.2	10.0	1.9	6.1	8.0	11.2	10.11
14-2A	Moro Cojo	(5)C	Loamy sand	100.1	80.6	7.6	2.4	10.0	2.5	7.0	9.5	11.9	10.11
40-2A	Hugo	(6)L-d1	Sandy loam	100.7	78.8	9.1	2.9	12.0	1.8	8.1	9.9	12.8	11.38
41-1A	San Andreas	(6)L	Sandy loam	100.0	77.4	9.0	3.4	12.4	2.2	8.0	10.2	13.6	11.94
6-1A	Moro Cojo	(6)L	Sandy loam	100.3	78.6	7.7	2.8	10.5	1.6	9.6	11.2	14.0	11.46
40-3A	Corralitos	1L	Sandy loam	101.0	75.5	9.5	3.0	12.5	2.0	11.0	13.0	16.0	14.02
9-1A	Moro Cojo	(6)L	Sandy loam	101.9	78.9	6.7	3.2	9.9	0.7	12.4	13.1	16.3	12.29
5-1A	Soquel	1L	Sandy loam	101.1	66.3	16.9	3.7	20.6	3.6	10.6	14.2	17.9	16.50
8-1A	Pinto	(7)M-d2	Sandy loam	99.9	62.4	17.1	4.6	21.7	2.9	12.9	15.8	20.4	13.51
39-1A	Pinto	(7)M-d2	Sandy loam	99.4	54.0	24.9	4.4	29.3	2.6	13.5	16.1	20.5	15.04
21-1A	Watsonville	(7)M-d3	Sandy loam	99.8	58.1	21.2	5.8	27.0	3.4	11.3	14.7	20.5	15.18
38-1A	Soquel	1M	Sandy loam	99.9	61.9	15.6	5.3	20.9	2.6	14.5	17.1	22.4	18.40
1-1A	Soquel	1L	Sandy loam	101.1	65.4	12.9	4.7	17.6	2.8	15.3	18.1	22.8	17.26
23-1A	Pinto	(7)M-d1	Sandy loam	99.7	59.4	17.2	4.4	21.6	3.0	15.7	18.7	23.1	14.70
27-1A	Botella	2M	Sandy loam	100.3	53.5	22.2	6.5	28.7	3.0	15.1	18.1	24.6	20.58
30-1A	Pinto	(7)M-d1	Sandy loam	100.2	52.7	22.6	13.0	35.6	2.1	9.8	11.9	24.9	16.39
11-1A	Pinto	(7)M-d2	Loam	100.7	49.5	26.2	5.6	31.8	3.4	16.0	19.4	25.0	15.75
2-1A	Pinto	(7)M-d3	Loam	100.4	48.7	25.9	7.7	33.6	5.2	12.9	18.1	25.8	18.15
24-1A	Hugo	(6)M-d1	Sandy clay loam	100.2	59.3	14.7	5.7	20.4	3.0	17.5	20.5	26.2	19.32
37-2A	Tierra	(7)M-d2	Sandy clay loam	100.9	60.9	13.3	4.7	18.0	3.1	18.9	22.0	26.7	20.01
27-2A	Botella	2H	Loam	100.3	50.7	22.7	6.8	29.5	4.4	15.7	20.1	26.9	20.02
3-1A	Hugo	(6)M-d1	Sandy clay loam	101.4	56.5	14.7	5.9	20.6	3.7	20.6	24.3	30.2	26.53
29-1A	Pajaro	1H	Loam	99.3	31.1	37.6	10.4	48.0	5.9	14.3	20.2	30.6	29.42
40-1A	Hugo	(6)H-d2	Sandy clay loam	100.7	54.4	14.7	4.9	19.6	2.9	23.8	26.7	31.6	23.08
7-1A	Watsonville	(7)H-d3	Loam	100.4	39.2	28.8	9.3	38.1	5.7	17.4	23.1	32.4	20.88
26-1A	Pajaro	1H	Silty clay loam	100.8	16.4	41.3	14.3	55.6	7.6	21.2	28.8	43.1	31.64
15-1A	Watsonville	3H-d3	Clay	99.8	22.5	26.1	9.1	35.2	6.8	35.3	42.1	51.2	32.69

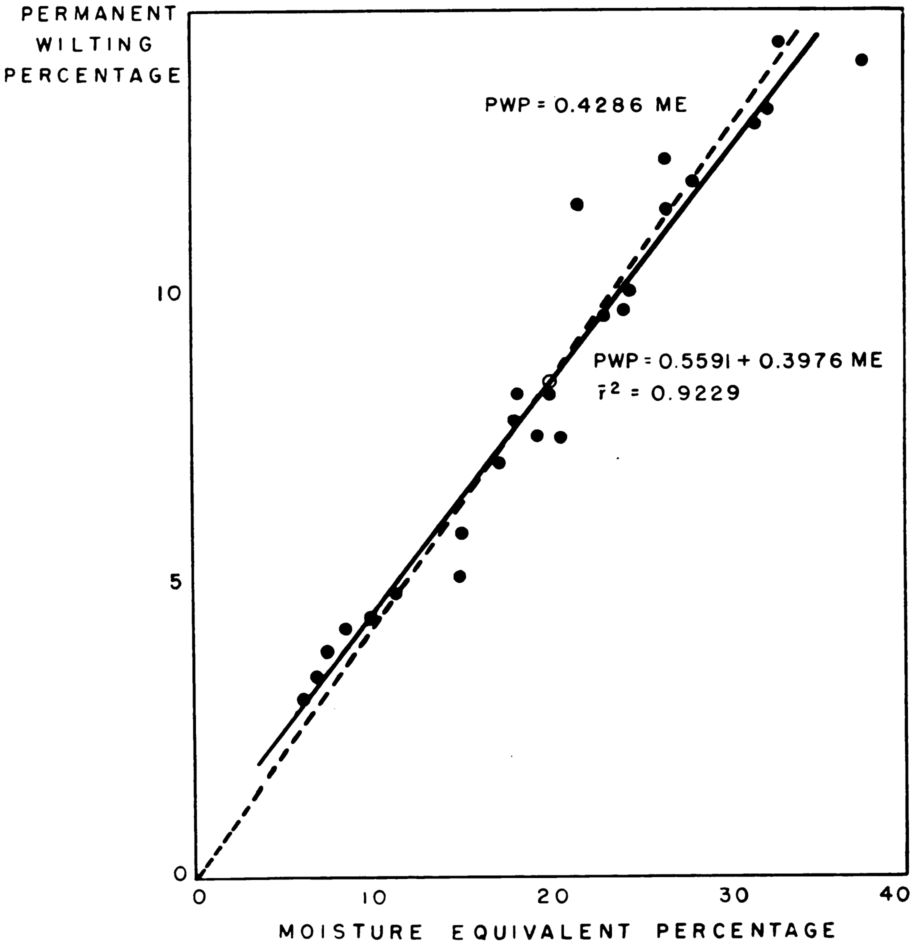


Fig. 3. Relation between permanent wilting percentage and moisture equivalent.

permanent wilting percentage from the moisture equivalent has proved to be notably untrustworthy in this respect.

Nevertheless, a correlation of the moisture equivalents and permanent wilting percentages given in table 1 of this same reference (p. 520) gives a coefficient of correlation of 0.954, indicating that moisture equivalent is a reliable indicator of permanent wilting percentage for these soils.

The relation between the permanent wilting percentage and the moisture equivalent percentage of the soils of the research area is shown graphically in figure 3. Regression analysis of this relation reveals that the intercept coefficient (0.5591) is not significant statistically while the slope coefficient (0.3976) is significant. The t-ratio for the intercept coefficient was 1.3133 and for the slope coefficient the t-ratio was 20.4515. The critical value at the 5 per cent level of significance for the t-ratios in this regression analysis was 2.060.

This permits a simplifying and more logical assumption to be made: It is assumed that the intercept coefficient is not significantly different from zero. Thus, adjusting the relation so that the intercept is zero, the permanent wilting percentage may be expressed in terms of moisture equivalent only:

$$PWP = 0.4286ME \qquad (2)$$

The line describing this adjusted regression equation intersects the abscissa and the ordinate at zero. Such an adjustment will reduce the degree of corre-

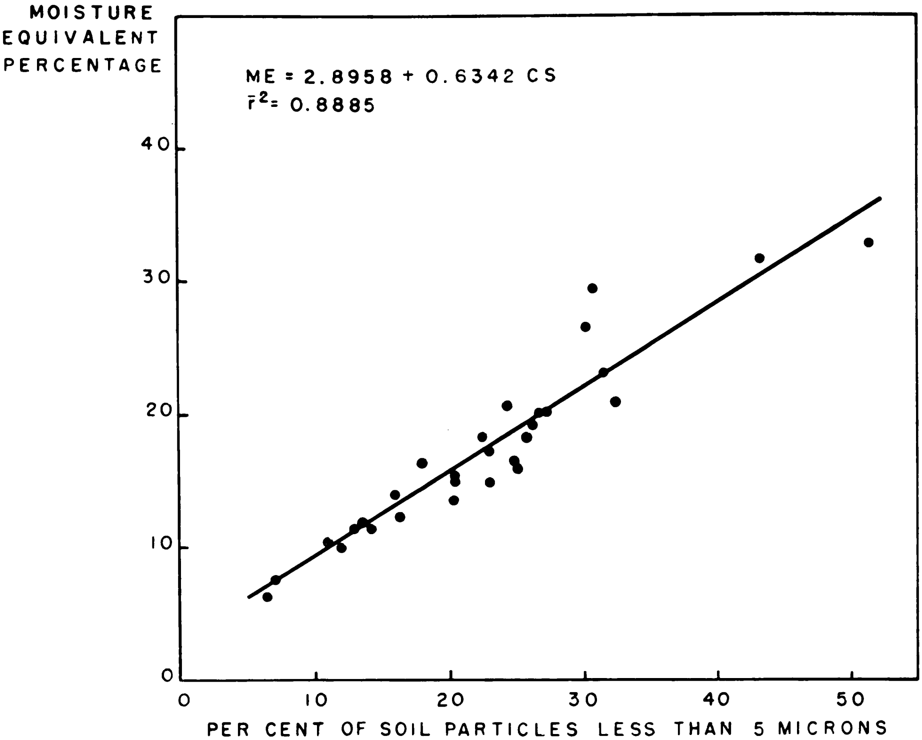


Fig. 4. Relation between soil texture and moisture equivalent.

lation, but only slightly. It is also to be noted that the adjusted value of the slope intercept—equation (2)—is not significantly different from the value of the slope intercept of the original regression equation—equation (1).

According to Veihmeyer (1938), the textural characteristics of the soil are perhaps the prime determinant of the moisture-equivalent value of a given soil. Other writers have demonstrated this important relation between soil texture and moisture equivalent (Joseph, 1927; Middleton, 1920). It is important, therefore, to examine the relation that exists between moisture equivalent and mechanical analysis in searching for a satisfactory soil variable.

A relatively high degree of association in the research area between moisture equivalent and particle size less than 5 microns suggests the possibility of using the percentage of the total soil weight having particle sizes less than 5 microns in diameter as a representative measure of a number of soil characteristics. The technique of examination consisted of scatter diagrams and correlation analyses between moisture equivalent and the several particle size fractions (fig. 4). The estimating equations obtained by the method of least squares and the respective coefficients of determination ($\bar{r}^2$), adjusted for sample size of 29, are shown below.

Fraction used in correlating with moisture equivalent	*Estimating equations*	*Adjusted coefficient of determination*	
Clay—C Per cent particles less than 2 microns	$ME = 3.7686 + 0.7887C$	$\bar{r}_3^2 = 0.8121$	(3)
Clay and Silt—CS Per cent particles less than 5 microns	$ME = 2.8959 + 0.6342CS$	$\bar{r}_4^2 = 0.8885$	(4)
Clay and Silt—CS′ Per cent particles less than 50 microns	$ME = 3.9332 + 0.3335CS'$	$\bar{r}_5^2 = 0.8234$	(5)

These results indicate a higher degree of association between moisture equivalent and particles of size less than 5 microns—equation (4)—than for either of the other two determinations.

Because of the high correlation indicated above between the moisture equivalent percentage and the permanent wilting percentage, the difference between these two soil properties as used in the available moisture function can be expressed in terms of moisture equivalent alone thus:

$$ME - PWP = ME - 0.4286ME = 0.5714ME$$

Because of the high correlation shown in figure 4 between the moisture equivalent and the clay-silt fraction, 5 microns and less in diameter (CS), this same difference between moisture equivalent percentage and permanent wilting percentage can be expressed in terms of soil texture thus:

$$\begin{aligned} ME - PWP &= 0.5714\ (2.8959 + 0.6342CS) \\ &= 1.6547 + 0.3624CS \end{aligned}$$

Small percentages of stone in the soil can be omitted from consideration because of the high degree of association between moisture equivalent and particle size less than 5 microns giving relatively greater importance to the fine soil particles.

The density factor in the available moisture function can be represented by a constant, 1.63, the average bulk density of 92 determinations in the research area. Variation from this average is small. Furthermore, bulk density is not highly correlated with moisture equivalent.

The available moisture function can now be written in terms of soil depth in inches, d, and the texture factor, CS, as follows:

$$\begin{aligned} \text{Available moisture} &= 1.63d(1.6547 + 0.3624CS) \\ &= d(2.6972 + 0.5907CS) \qquad (6) \end{aligned}$$

Thus, the four soil properties most important in determining available moisture can be expressed in terms of the soil texture variable.

Organic matter and chemical composition of the soil also have been considered as having varying degrees of importance in relation to moisture retention and to the manufacture and storage of nutrients. Although the degree of these effects is controversial, a careful review of the literature in this field has been the basis for the following assumptions:

1. The high degree of interdependence existing between the effect of organic matter on the moisture equivalent of a soil and the finer soil particles is adequately included in equation (4). The additional effect directly attributable to organic matter is assumed not to be significant for the soils reported herein.
2. Because the soils of the research area under study do not present conditions which come within a significant range of sodium-saturated problem soils, the effect upon moisture equivalent of variations in the adsorbed bases may be ignored without introducing significant error.
3. The good correlations of yields with moisture equivalent of the surface soil probably "in part are conditioned by a hidden correlation between texture and the fertility of the soil, the latter resting mainly in the surface soil."[5]

The research described in the foregoing discussion not only confirms the previously recognized relation existing between soil texture and moisture equivalent, but establishes a new simple measure of this relation which is a workable and highly useful variable applicable in research. The strategic position of this soil texture variable may be summarized for the research area as follows:

1. Soil texture, to a great extent, characterizes the soils of the area as a physical medium for plant growth.
2. Soil texture, although already defined in highly complex quantitative terms, may be expressed approximately but more simply as a single-valued variable by the percentage of particles 5 microns in diameter or less.
3. The symbols, C, L, M, and H, commonly used in the field by the Soil Conservation Service in classifying textures can thus be quantified by the average of and by the range in the percentage of particles 5 microns in diameter or less. (Average percentages: C = 7.75, L = 14.04, M = 23.51, and H = 37.41.) This established quantitative relation between textural classes is a highly useful device in the analysis of economic productivity as will be demonstrated below.
4. The high correlation in the research area between the percentage of soil particles 5 microns or less and moisture equivalent provides a basis for using, in that area, moisture equivalent interchangeably with the texture factor as a soil variable.
5. Soil texture can be depended upon to represent, fairly reliably, a number of the other physical properties of the surface soil.

Soil texture and moisture equivalent are limited, however, in their repre-

[5] Jenny, Hans. Memorandum to Raymond G. Bressler, March 9, 1956.

sentation of the soil profile. It is necessary, therefore, to search further for a single-valued variable which will simplify, characterize, and quantify the soil profile.

Selecting the Profile Variable

The soil profile is distinctly more difficult to quantify and to express in terms of one or a small number of variables than is soil texture. Furthermore, it was observed, subject to further analysis, that texture characteristics and profile characteristics are interrelated in their joint regression with production.

Profile Moisture Equivalent. As a first step in the search for one or more variables to represent the soil profile, a weighted average *profile moisture equivalent* was used to represent and to describe, without evaluation, the characteristics of the soil profile. Separate moisture equivalent determinations were made for each distinct horizon encountered in the 81 profiles which were sampled. Thickness of horizons was measured in each profile. The average profile moisture equivalents for the profiles were calculated, weighted by horizon thickness.

Range in Moisture Equivalent. A second indicator of the characteristics of the soil profile was calculated from the moisture equivalent data. This indicator is the *range in moisture equivalent* present in a particular profile. This range in values of the moisture equivalent was considered to be, more specifically than the weighted average, an indicator of the stage of development of a particular soil.

These two measures were examined and analyzed to determine if their use would permit separation of the effects of the soil upon productivity from the effects of various conservation and other farm practices. Correlation analysis between apple production and profile moisture equivalent, and between apple production and range in moisture equivalent, failed to explain the cause of variation beyond those explained by the texture or moisture equivalent of the surface soil.

The Storie Profile Rating—"Factor A." Recognizing the desirability for further search for a simple descriptive and quantitative expression of the soil profile characteristics, factor A of the Storie Soil Rating Index has been selected, provisionally, for this purpose. Unpublished values of the profile ratings of the soils of the case farms were made available by the Department of Soils and Plant Nutrition, University of California. These profile ratings were used in the joint regression analysis described in a later section of this report.

Because of inadequate yield information for soil textures other than "medium" at the 50–60 Storie Profile Rating level, the assumption was made that soil texture differences at the 95–100 Storie Profile Rating level would produce the same percentage differences in yield as at the 50–60 Storie Profile Rating level. Further research will be required to justify this assumption fully. Nevertheless, the more serious of the limitations of the Soil Rating Index have been eliminated by empirical determinations of some of the more important functional interrelations between the soil productivity factors.

DEVELOPMENT OF THE AGE AND YIELD VARIABLES

Collection of Age-Yield Data by Land Class

Most of the data used in the research are primary data obtained either in the field by direct observation or from farmers and their written records, bills, memoranda, and so forth. As early as 1947, a schedule was filled out for 43 producers carrying out various conservation practices within the Pajaro Soil Conservation District. Of these producers, 33 were growers of nonirrigated Yellow Newtown apples, the crop used as an indicator in this study. The schedule called for historical information on land utilization; apple production by variety; orchard acreage by variety, age, and planting pattern; and detailed information on tillage operations, conservation practices, fertilizer, spraying, and other inputs in terms of man-, machine-, tractor-hours, and materials.

In the spring of 1948, a soil conservation survey was made of each of the farms for which the schedule was completed. The unit areas of this land classification were delineated upon an aerial photograph of each of the farms enlarged to approximately 16 inches to the mile. The scale of each of the aerial photographs was determined precisely by measurement with a steel tape in each orchard. Each unit area was given the code designation corresponding to the system described in the *Soil Conservation Survey Guide* (Wohletz, 1948). On another copy of the aerial photograph, enlarged to the same scale, a detailed delineation of the land utilization pattern was outlined. Supplementing the schedule data, every normal, stunted, missing, dead, or replanted tree in the entire sample was counted and classified by observation in the orchards. This meticulous work was necessary for the kind of measurements contemplated. Any lower standard would have resulted in the abandonment of the project. A transparent copy of the land classification map of each farm of the sample superimposed over the land utilization map made possible a tabulation of 68 observations of land-use acreage and yields by land class and age of orchard for a six-year period (1944–1949).

Difficulties in Obtaining an Adequate Sample

Some of the most important locations for obtaining observations of yield are at the margins of transference between types of land use. In these locations, such observations are frequently impossible because of the small number of farms producing the crop being sampled—in this case, Yellow Newtown apples. At best, in such locations, samples are inadequate. Furthermore, some of the complex relations uncovered in the analysis could not be foreseen in the research planning stage. For this reason, again, sample data were insufficient or not available to make, with a satisfactory degree of certainty, all of the measurements embraced in the objectives of the study.

Consideration of Other Variables

In addition to these four variables—yield, soil texture, profile rating, and age of orchard—a slope variable and five conservation and farm-practice variables were recognized as complicating the analysis. The effects of these variables upon the results of the soil analysis could not be determined at this stage of the research. The problem would have required successive approximations involving all ten variables in order to adjust the correlations pertaining to the soils and tree-age variables. For the purpose of interpreting the results presented in this report, therefore, a typical level of farm practices for each age-profile-texture combination was assumed pending completion of an analysis in progress of the variability of farm practices (particularly conservation practices) and their relation to production.

TABLE 3

RELATION OF NEWTOWN APPLE YIELD TO AGE OF TREES, LOWER PAJARO VALLEY, CALIFORNIA, FOR SOILS HAVING 100 PROFILE RATING AND MEDIUM SOIL TEXTURE*

Age of trees, years	Yield, 36-pound boxes	Yield as a percentage of yield at 45 years of age
6	0	0
10	227	22.7
20	648	64.8
30	890	89.0
40	991	99.1
45	1,000	100.0
50	988	98.8
60	920	92.0

* Calculated from equation (8).

JOINT REGRESSION ANALYSIS OF INTERRELATED VARIABLES

Method as Determined by Characteristics of Variation

Of the group of variables analyzed herein—soil profile factor A, soil texture, and age of orchard on the one hand and apple yield on the other—two were found to have curvilinear relations with yield, and all three were found to be interrelated. That is, the problem presented is one of joint functional regression. Graphic analysis of these relations has provided preliminary results that merit presentation. The technique of analysis used was similar to the successive graphic approximation method as developed in Ezekiel (1947).

Procedure

Observations on yield were divided into three major segments based on profile groups as used by the Soil Conservation Service between February, 1948, and April, 1952. One segment is the medium-textured soils of the (7) profile group having Storie profile ratings ranging from 50 to 60. Another segment includes the light-textured soils of the (6) profile group having a profile rating of 70. The third segment includes profile groups 1 and 2 having profile ratings ranging from 95–100. A quantitative relation is thus

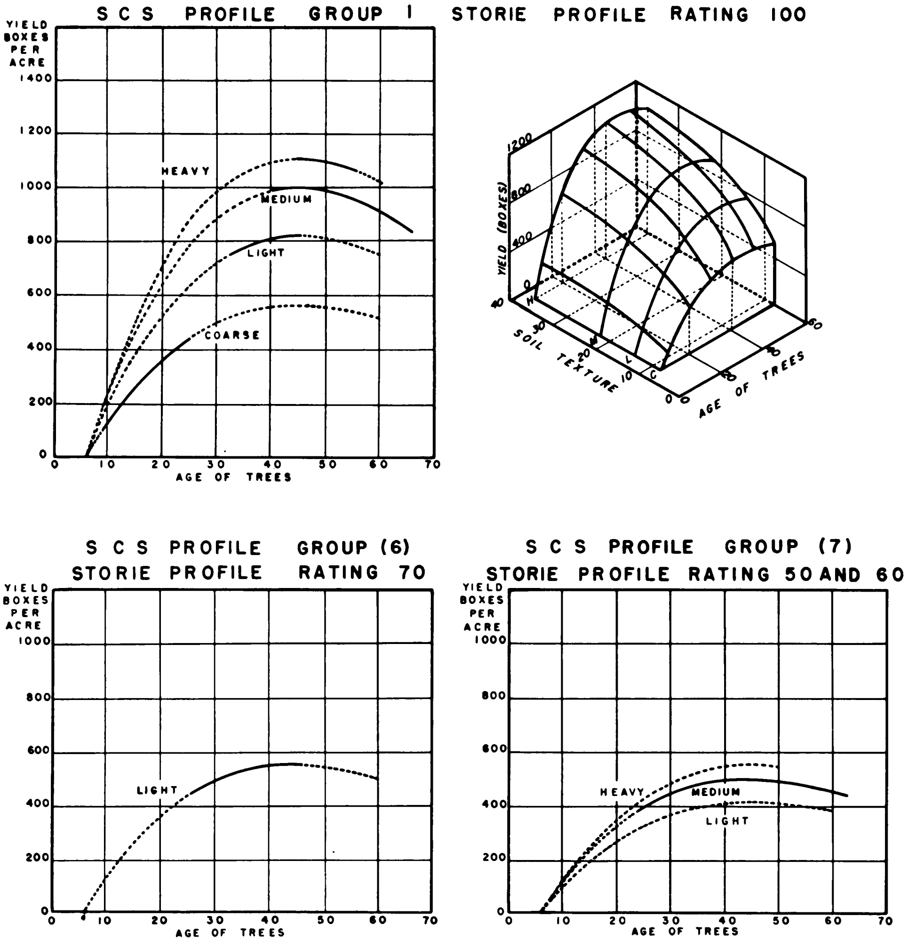
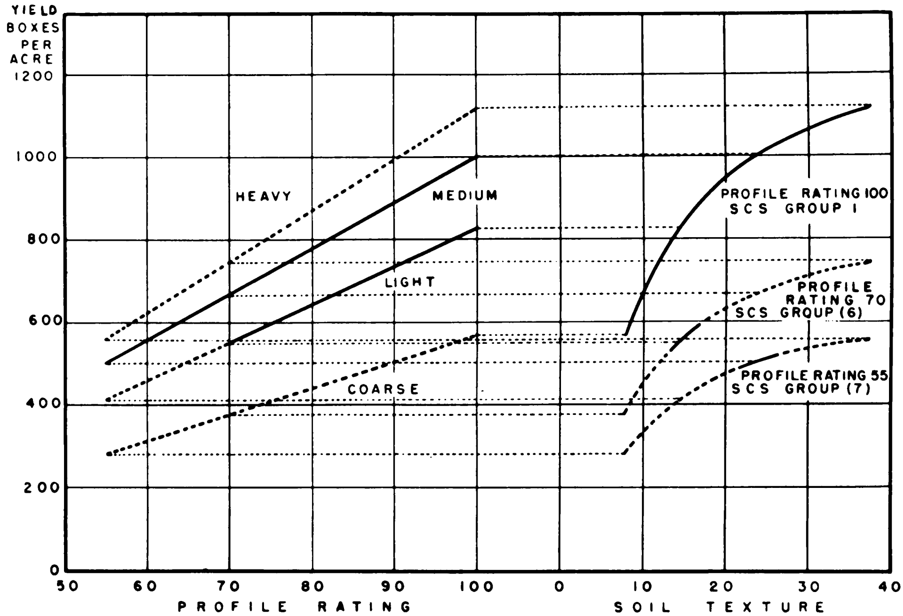


Fig. 5. Relations between Newtown apple yields and orchard age by soil profile and soil texture groups.

established between the Storie Profile Rating and the Soil Conservation Service profile grouping.

The observations of Yellow Newtown apple yield, soil texture, profile rating, and age of trees were recorded on strips and sorted. The groups containing greater numbers of cases were used first in plotting preliminary curves of relation between yield per acre and the different variables. Segments of the several curves were combined to develop two surfaces of three variables each as shown in figures 5 and 6. The portions of the curves represented by solid lines are fairly well supported by measurements of the variables. Portions not well supported are dotted. Discrepancies between the different surfaces were reconciled by adjustments to bring about continuity and consistency of relation. To aid in this process, mathematical expres-



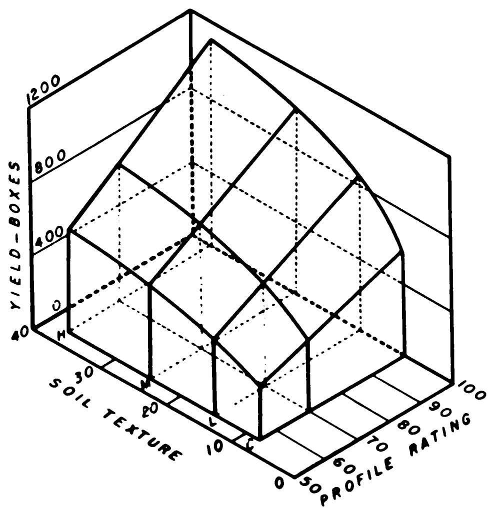


Fig. 6. Relations between Newtown apple yields, soil profile rating, and soil texture—orchard age equal to 45 years.

sions were fitted to the graphical surfaces (see tables 3–6). Strict adherence to fitting the curves by least-squares method was abandoned because of the complexity of the functions that had to be developed together with the limitations of the available data.

TABLE 4
RELATION OF NEWTOWN APPLE YIELD TO SOIL TEXTURE, LOWER PAJARO VALLEY, CALIFORNIA, FOR SOILS HAVING 100 PROFILE RATING, ORCHARDS 45 YEARS OF AGE

Soil texture		Estimated yield per acre	
S.C.S. textural group name and symbol	Percentage of soil having particles 5 microns or less	Number of 36-pound boxes	Relative to medium texture, per cent
Very light, or coarse (C)	7.75	566	56.6
Light (L)	14.04	823	82.3
Medium (M)	23.51	1,000	100.0
Heavy (H)	37.41	1,118	111.8

TABLE 5
RELATION OF NEWTOWN APPLE YIELD TO AGE OF TREES AND TO SOIL TEXTURE AND SOIL PROFILE GROUPS

Age of trees	Estimated yield in 36-pound boxes by soil texture and profile group							
	Group 1—100 profile rating				Group (6)—70 profile rating	Group (7)—55 profile rating		
	Coarse	Light	Medium*	Heavy	Light	Light	Medium	Heavy
	1	2	3	4	5	6	7	8
6	0	0	**0**	0	0	0	0	0
10	128	187	**227**	254	123	94	114	127
20	367	533	**648**	724	353	268	325	364
30	504	732	**890**	995	484	368	447	499
40	561	816	**991**	1,108	539	409	497	556
45†	**566**	**823**	**1,000**	**1,118**	**544**	**413**	**502**	**561**
50	559	813	**988**	1,105	537	408	496	554
60	521	757	**920**	1,029	500	380	462	516

* This column is calculated from equation (8).
† Columns 1, 2, 3, and 4 on this line (45 years) are calculated from equation (9) (see text).

Estimating Equations

The equations of relation and a statistical constant developed during the process of constructing figures 5 and 6 and tables 3 to 6 are as follows:

$$X_1 = K \frac{[X_{1(M)(100)}]\ [X_{1(45)(100)}]}{1{,}000.0} \qquad (7)$$

X_1 = Yellow Newtown apple yields for any given age of tree, soil texture, and soil profile. *This is the general equation of relation of the three independent variables to the dependent variable, yield.*

$X_{1(M)(100)}$ = Yellow Newtown apple yield per acre for trees of the same given age as for the dependent X_1 on soils of medium texture having a profile rating of 100.

$X_{1(45)(100)}$ = Yellow Newtown apple yield per acre for trees 45 years old of the same soil texture as for the dependent X_1 but having a profile rating of 100.

1,000.0 = The denominator of the general expression, the estimated yield common to the two functions presented below, equations (8) and (9): the yield from 45-year-old Yellow Newtown apple trees growing on medium-textured soils with a profile rating of 100.

K = A statistically determined constant that has been calculated for each of the profile groups analyzed (table 6) as follows:

1. Yield was plotted as a dependent variable against age for each texture-profile combination. Mathematical functions were fitted by successive graphic approximation for each combination. Equation (8)—yields from soils of medium texture and profile rating of 100—was developed from this step of the procedure.

TABLE 6
THE PROFILE CONSTANT

S.C.S. profile group	Storie profile rating	Values of K*
1	100	1.000
(6)	70	0.661
(7)	55	0.502

* For definitions of the notation and derivation of K, see text.

2. Yield was plotted as a dependent variable against texture expressed as a per cent of particle sizes 5 microns or smaller for each profile age group. Equation (9)—yields from 45-year-old apple trees on soils with profile rating 100—was developed from this step of the procedure.
3. Yield ratios were calculated between corresponding texture age groups for the different profiles using soils with profile rating of 100 (Soil Conservation Service profile group 1) as a base.
4. All yield ratios calculated in step 3 were approximately equal for the texture and age subgroups of a given profile group. This led to the assumption that these ratios, averaged for each profile, could be applied to the calculations of yield for profile rating 100 to obtain the corresponding yields in other profile groups.

The equation of relation for Yellow Newtown apple yields per acre and age of tree on soils of medium texture having a profile rating of 100 is:

$$X_{1\,(M)(100)} = 0.0063\,X_2^3 - 1.2731\,X_2^2 + 75.8848\,X_2 - 410.8376 \qquad (8)$$

$X_{1\,(M)(100)}$ = Defined above.
X_2 = Age of orchard.

Calculation of yields by the use of this equation is presented in table 3 and in boldface type in column 3 of table 5.

The equation of relation for Yellow Newtown apple yields per acre and soil texture for trees 45 years old on soils having a profile rating of 100 is:

$$X_{1\,(45)(100)} = 0.0327\, X_3^3 - 2.8879\, X_3^2 + 91.8178\, X_3 + 12.6450 \qquad (9)$$

$X_{1\,(45)(100)}$ = Defined above.

X_3 = Soil texture expressed as a per cent of particles 5 microns or less.

Calculation of yields by the use of this equation is presented in table 4 and in boldface type for trees 45 years old in table 5.

Interpretation of Results

Although a degree of confidence is established by these preliminary results, the major value of the experience gained to this point is in the development of methodology. Assurance of the validity of the final conclusions—particularly those pertaining to the separate variables—can only come with research planned on the basis of this experience.

Measures of Reliability. Testing the estimating system described above, about 44 per cent of the variation in yields can be accounted for in terms of variation in the soil and tree-age variables. A correlation between yields estimated by the equations and observed yields gives coefficients of correlation and of determination as follows:

$$\overline{R} = 0.662; \overline{R}^2 = 0.439$$

Tests of estimates of yield based upon a preliminary ten-variable regression analysis indicate that about 87 per cent of the variation in yields can be accounted for when slope and management practice variables are included with those being treated here, coefficients of multiple correlation and determination being as follows:

$$\overline{R} = 0.930; \overline{R}^2 = 0.866$$

Use of Results. The uses that may be made of the results are twofold in nature:

First, this technique may be used to measure soil productivity in the greater problem of measuring direct economic benefits of soil conservation practices. The measure of productivity developed herein may be so used in future investigations. The measures developed at this point represent productivity of the soil by soil texture and profile groups for typical input of other factors. Measures that account for variation in input, however, are necessary in evaluating direct economic benefits from soil conservation practices. Therefore, the use of these measures in evaluating economic benefits from soil conservation is not presented in this discussion.

Second, this technique may be used directly to quantify the physical character of soils and thereby measure productivity in terms of yields of specific tree crops. As developed in this paper, the technique applies only to a particular variety of apple grown within a relatively confined area. But methodology has been established that is applicable to a wider variety of situations. The specific equations of relation developed in this discussion are probably not applicable to apple production—or even Yellow Newtown apple production—in other areas unless soil, climate, topographic, and management factors are closely akin to those found in this research area. There is no reason, however, why a similar investigation will not produce equally useful equations of relation for measuring productivity in other areas. Future experience may produce equations of relation that will permit greater generalization and be of wider applicability.

Thus, the results of this part of the study are more "physical" than "economic." The equations of relation provide measures of physical productivity for the particular crop and area under study. This measurement provides a useful basis for evaluation of economic productivity in the same area. A methodology has been presented that may be viewed as an end in itself—if only problems of physical productivity are of concern—or as a point of departure for the analysis of economic productivity.

One point to be emphasized is that caution should be exercised in designing the sample for future investigations. Unusual difficulties are presented in obtaining a satisfactory sample for such a study. Preliminary survey—to indicate the nature and extent of variability in soil conditions—would aid in providing more nearly adequate representation of all categories present in an area. Care must also be exercised in selecting an area of study that is reasonably homogeneous to facilitate the inclusion of all categories essential to derive the desired equations of relation. Such caution will permit developing equations of relation for application over a wider range of situations.

The possible use of this technique of analysis for measuring productivity in areas characterized by annual crop production should not be overlooked. Information on additional variables, particularly the variation in climate and management factors over time, would need to be included. This would complicate the analysis but would not preclude use of the technique.

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