Soil Surveys: Review of Data-Collection Methodologies, Confidence Limits, and Uses

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The scientific basis of the soil survey is that the locations of soils on the landscape have a degree of predictability. Soil surveys are reasonably accurate and affordably feasible because this soil-landscape association possesses a degree of correlation that is high enough to allow inferences and predictions of soil behavior. The soil surveyor uses a working model of soil genesis on the landscape and tests it through observations. Inferences derived from these observations are extrapolated to the boundaries beyond which the inferences have been judged by the soil scientist to be invalid by virtue of changes in one or more of the factors (e.g., slope, vegetation, parent material) responsible for controlling soil genesis. In most areas, the natural scatter or range of soil properties and the variability of the soil-landscape precludes the delineation of taxonomically pure soil units. This results in inclusions of both similar and dissimilar soils within the soil-unit delineations. Soil scientists recognize these inclusions and describe them as part of the map unit. The composition and variability of soil map units are discussed with examples of how these map attributes can be quantified to provide confidence limits for predictions of soil behavior. It is emphasized that the primary objective of most soil surveys is not to map delineations having taxonomic purity but to provide the user with information as a basis for judgments about soil potentials and behavior for various land uses. Studies and experience have shown that the uniformity of such map units for interpretive purposes is much higher than is their taxonomic purity.

Soil surveys are one of the most widely available forms of geotechnical information. Since 1955, modern soil surveys have been prepared for more than 570 million hm^2 (1.4 billion acres), or nearly 65 percent of the land area of the United States. In addition, there are many soil surveys that were prepared before 1955. Data from these soil surveys can be obtained in the local offices of the Soil Conservation Service, U.S. Department of Agriculture.

It is essential that the definition of soil used by pedologists be distinguished from that in common use in engineering and geology. In the latter fields, soil refers simply to the unconsolidated earthy materials above bedrock. The pedologist, however, defines soil as a three-dimensional natural body at the earth's surface that supports or is capable of supporting the growth of plants, i.e., that part of the earth's crust that is subject to the influence of soil-formation factors.

In soil surveys, the soil horizons within the upper 2 m are observed and described. The characteristics of materials below the soil are sometimes described, but only where sufficient observations have been made to provide reliable information.

USING SOIL SURVEYS IN PLANNING TRANSPORTATION SYSTEMS

Soil surveys can provide data of value in planning the location and construction of highways and are among the most useful sources of information for planning the land uses that will be served by a highway (1).

The design of highways requires that many soil properties be measured by laboratory or field tests or by observations. Many of the measurements that must be made are expensive, e.g., moisture-density relationships and shear-strength, permeability, and consolidation tests.

Because of the time and expense required, intensive investigation, sampling, and testing are done only for design purposes after a site has been selected. It is not practical to make detailed studies of each alternative site for planning.

In planning, however, it is important to have some indication of soil properties over a wide area. This makes it possible to consider other land uses and alternative locations for highways. Data from soil surveys can be obtained by the transportation engineer without extensive work and expense.

Soil surveys provide a general indication of compressibility, density, strength, and bearing capacity. They also provide more specific information about other soil properties and attributes, such as drainage and moisture regime; ease of excavating and hauling; and slope, erosion hazard, and depth. In addition, the following soil properties important to highway planning are indicated by the soil horizon: (a) textural class; (b) mineralogy; (c) soil chemistry, including pH and salt content; and (d) presence of coarse fragments that might affect excavating, spreading, and compacting.

From these properties, general interpretations can be made, including (a) plasticity characteristics and classification according to various engineering and textural classification systems, (b) potential for frost action, (c) potential for shrink-swell, and (d) hazard of flooding.

Several of these properties, such as depth to bedrock and soil slope, are measured directly at sampling points within each map unit. Other items are interpreted or inferred from the data collected and the observations made.

Ratings of soil limitation and potential are prepared on the basis of these soil properties. The ratings provide a quick means of comparing soil map units for numerous land uses.

Although many of the soil engineering data provided in soil surveys are not measured directly and may not provide the precise numbers needed for design analyses, these data do provide valuable information for planning design activities. When supplemented with geologic maps, soil profiles can provide a basis for planning the detailed investigations necessary to obtain design data. Examples include the type of investigation and the sampling tools needed, the approximate location of contact zones between differing conditions, and construction season length as related to temperature and weather conditions.

The methodologies of collecting soil-survey data and information, analyzing the composition of soil map units, and evaluating the variation or range of soil properties are described below. Understanding these methodologies should help highway engineers and other interpreters of soil-survey information to use soil surveys more effectively, considering the limits of their intended use and the confidence limits of the information.

DATA COLLECTION

The key to making use of the data in soil surveys is to understand exactly what procedures were used to obtain them, the kinds of data collected, and the amount of data collected per unit area. Soil surveys differ widely in the kinds and amount of data collected. The intensity of data collection depends on the objective of the survey.

Scientific Basis of Soil Surveys

The soil survey is basically a data-collecting activity. Soils rarely occur randomly on the landscape, and they can be stratified and mapped with some degree of reliability. Thus, the soil survey is unlike many surveys of either fixed or infinite populations. Because of cost and time constraints, a random data-collection technique that allows every member of the population of soils on the landscape an equal chance of being sampled is neither practical nor necessary in most soil surveys. Therefore, the soil scientist purposely practices a form of sampling bias or stratification of landscapes in selecting the sample sites from which inferences will be extrapolated to derive the soil boundaries. In essence, soil scientists stratify the universe (population of soils) before them in an effort to segregate the landscape into classes that have definable ranges of properties. The geologist also practices this technique out of necessity, producing maps that have a degree of reliability that is based on the association of geologic formations with landscapes or geomorphic units.

The purpose for sampling the soil, therefore, is not simply to obtain a number of random samples from which conclusions will be drawn to make a map when subjected to statistical techniques but rather to either confirm or reject the soil scientists' hypothesis of what soil is expected on a given landscape unit. Soil mapping then is basically the ability of the soil scientist to develop a working model of soil genesis on the landscape and test it by observations.

The soil surveyor observes soil by excavation (borings, for example) only at certain points on the landscape. But, because soils form a continuum on the landscape, it is necessary to infer through judgment where one soil ends and another begins. Therefore, the delineation of soil map units and the interpretations about their behavior are derived from inferences extrapolated from very small samples. More than 99 percent of the soil delineated by the soil surveyor in making a soil map is not observed below the surface. Yet the association of different kinds of soils with certain landscapes possesses a degree of correlation that is high enough to allow inferences and predictions of soil behavior to be made.

Although the soil scientist cannot record what the soil is like at every point on the landscape, those who commission and use soil surveys often want such information (2). They want to be able to infer or predict the nature of the soil at all places (even though relatively few observations were made). And, although the essential objective of soil surveys is the collection of information, many users of this information do not understand the way in which it is obtained and the way in which the interpretations of soil behavior are inferred. Information and inferences made from single observations are extrapolated to the boundaries between the map unit and other units (in which similar observations were made). Therefore, the information is not site specific for each point within a map-unit delineation. Efforts to use this information as site specific for small areas cause substantial problems. The misunderstanding of the soil survey and the arguments that follow are due largely to these problems. Understanding that on-site studies are needed for many site-specific applications would do much to prevent these problems.

The scientific basis of the soil survey, therefore, is that soils and their location on the landscape are predictable (to be sure, some more than others) to an experienced soil scientist who has knowledge of the geology, climate, and landform patterns of the area. In essence, the soil scientist must be able to read and predict the relationship between the landscape and the soils that have formed on it. The sampling technique, therefore, is used to confirm the prediction based on the soil scientist's model. If the observed soil profile fails to confirm predictions, the soil scientist must develop a new working model through further study.

Making Soil Surveys

Preliminary Planning

Preliminary planning of soil surveys centers on discussing and reaching agreement on the kind and amount of data that must be collected. This question is decided on the basis of the land use for which the soil survey is to be prepared.

Soil surveys are prepared for a wide variety of land uses. Categorizing all soil surveys as agricultural has never been appropriate. In some areas, soil surveys are designed to provide data to guide rapid urban development, in other places, they are used to plan irrigated agriculture, woodland, or other land uses. Obviously, a given soil survey can provide useful data for many land uses. However, more data are required for some land uses than for others. For example, in an area of intensive agriculture in California, a soil survey having a scale of 1:24 000 may be adequate for planning crop sequences, fertilizer needs, drainage requirements, and other management practices within fields, but a scale of 1:20 000 or 1:15 840 may be needed to plan the encroaching urban development.

As this implies, the mapping scale is a key early choice in planning soil surveys. It is usually based on the minimum area for which specific soil data are needed for decisions about the use and management of land.

Preliminary Field Investigations

Before operational mapping is done, existing geologic surveys, old soil surveys, and other sources of soil information, along with aerial photographs and topographic maps, are studied to learn as much as possible about the soils and landscapes. Also, the local relationship between soils and plants is studied to ensure that the useful indicators of soil differences are identified.

In preliminary field investigations, some soil profiles and certain small tracts can be given more intensive study than is done in the normal mapping process that is used in the operational stage of the survey. These intensive studies will cover only a portion of the survey area. Their main purpose is to determine the pattern of soil variation in each of the physiographic areas of the survey area (3). Some of these physiographic areas have a complex pattern, whereas others possess a more uniform soil pattern. In the more-uniform areas, it usually is not necessary to collect as many data during operational mapping as in the more-complex areas.

Based on these careful early investigations, the soil map units are described in as much detail as possible before operational mapping. In these descriptions, the pattern of soil occurrence and the relationship of soils to landscapes are emphasized and the proportion of each soil is estimated. During this stage, tentative soil surveys are prepared for the areas studied.

Operational Mapping

Operational mapping requires data collection by three main approaches: (a) inferences drawn from landforms and vegetation, (b) on-site borings, and (c) laboratory characterization.

Soil surveys are made by traversing the land, largely by walking. The surveyor knows the geologic formations in the area. The kinds of vegetation are identified. The surveyor has the benefit of the preliminary field investigations and soil descriptions. In addition, the surveyor draws on his or her own understanding of the relationships between soils, landscapes, and vegetation.

The first step is to use preexisting relationships to infer which soils occur in a given area. The value of inference as a form of data collection has not previously been given proper emphasis in descriptions of mapping procedures. Because it is never practical, regardless of the scale of sampling, to sample all the soil, the assumption is that the areas between samples were properly characterized by the samples taken. This point will be addressed in greater detail below.

As the surveyor traverses the landscape, he or she studies the landforms and other features and infers the soil most likely to exist on each landscape segment. Borings are made to identify the important soil properties and classify the soil. The borings test the inference made. At these boring sites, the type, thickness, structure, and color of each soil horizon are determined. Textural classes are estimated by field procedures. Quick field tests of soil pH and salinity are made as appropriate. Based on these borings and the information derived from them, the kind and sequence of horizons are identified and the soil is classified into the appropriate class or taxa. From this information, the proper soil map unit is decided. The edges of the soil map unit are located by judging the location of transition in one or more of the factors (e.g., slope, vegetation, or parent material) that control soil genesis.

The surveyor sketches the soil boundaries as far ahead as possible along the transect being followed. Then, as he or she proceeds, the accuracy of the projected location of soil boundaries can be determined. This process is essential because it is the only rational method of deciding how far apart the transects should be. The accuracy in projecting ahead is the same as the accuracy in projecting to the side of the transect.

During mapping, the soil observed in a very high proportion of the borings should conform to the surveyor's inferences. Where it does not conform, additional borings are made to determine the reasons for the departure.

The number of borings made is highly variable in a given soil-survey area. It is based on the judgment and experience in the area of the soil surveyor and on the complexity and predictability of the soil-landscape relationship. For example, on a 10-hm^2 (25-acre) moraine front slope where the soil pattern is variable, 10-15 borings may be needed to determine the pattern of soil variation. On a 2000-hectare (5000-acre) lacustrine area, where there is little soil variation, 10 borings may be sufficient.

Laboratory characterization data are obtained from a limited number of soil profiles in a soil survey area. The main purposes for obtaining these data are to provide a basis for improvement of the ability to make accurate field estimates of soil properties and to provide benchmarks for use in classifying and interpreting the soils. Some properties, such as cation exchange capacity, are correlated or associated with observable properties, e.g., pH or texture, and it is necessary to check this correlation occasionally. Laboratory testing is done for similar reasons to determine the engineering index properties of major horizons of selected soil series.

Selection of Sample Sites for Laboratory Characterization and Field Classification

Sample sites are selected—whether for laboratory characterization or for borings for field soil classification—to represent a unique landform position in which a specific kind of soil is expected. For efficiency in mapping, those landform positions most representative of the delineation are chosen. However, positions that differ from the norm must also be examined to determine whether or not the soils expected in these positions actually occur there.

Presentation and Display

Some of the data collected during soil mapping are summarized in soil map unit descriptions. Laboratory data—and, in a few cases, transect data—are presented in tables. By far the greatest volume of data is collected from regular borings and by inference from the landforms and vegetation. These data are presented in the map-unit descriptions, which are thus the most useful reference.

In a map-unit description, the user will find a discussion of the proportion of the delineated area in which the dominant soils occur along with a description of the nature and occurrence of other component soils known to occur within the delineation and their position in the landscape. The user is thus alerted to expect small areas of soils in certain portions of the map unit that are different from the dominant soil from which the delineated map unit is named.

Basis for the Predictive Value of Soil Map Units

Once a soil classification scheme has been developed, data obtained from soil landscape studies can be correlated with classification units. Thus, once soils are classified, their behavior can be predicted or their characteristics can be interpreted with some degree of confidence. This requires that data be collected on the observed behavior of the soils in each of the land uses for which predictions of behavior are made. In other words, to the fullest extent possible, those correlations between soil properties and soil behavior that are assumed to be true are checked against actual soil performance.

The behavior of the soil map units can thus be predicted for a variety of uses with a degree of confidence. But before we can know the confidence limits of our predictions about these map units, we must understand their composition and variability.

COMPOSITION OF SOIL MAP UNITS

Soil Map Units Versus Soil Taxa

Even though soils form a continuum on the landscape, the objective of a soil survey is to break this continuum into a reasonable number of segments or units. Each unit delineated on the landscape has limited and defined ranges in properties so that one can make quantitative interpretations and predictions of soil behavior (4).

Problems and confusion often arise, however, when the distinction between the concepts used to differentiate or define the soil taxa and the map units themselves is not clear. The taxa are conceptual, but the map units are real and may possess characteristics and properties outside those used as differentiating criteria in the taxonomic scheme. This distinction is especially critical when the taxon and the delineated map unit on the landscape are identified by the same name. Furthermore, because the natural scatter or range of soil properties within a particular landscape usually results in some soils falling outside the dominant taxonomic class for which the map unit is named, soil map units usually contain inclusions of more than one taxon.

Of the six categories in Soil Taxonomy (5), the soil series represents the lowest, i.e., the category having the largest number of differentiae and classes (taxa). There are more than 12 000 soil series recognized in the United States.

Each series is a conceptual image of a specific soil that has a common suite and range of differentiating properties as well as a fixed arrangement of diagnostic horizons. The series concept does not imply any geographic or spatial attributes or any specific aspect on the landscape. The series taxon, therefore, is a mental image or concept of a soil body that is known to occur in certain geographic areas associated with specific parent materials or geomorphic features or both. The soil scientist, in observing the landscape, tries to delineate those areas where the concept of a particular soil series applies. For practical purposes, soil series are further subdivided into phases of slope, erosion, stoniness, substratum, and other properties not diagnostic at the series level, so that differences significant to the uses of the soils within the series can be identified. In mapping the soil, a boundary of the conceptual soil body is located in those places where there is a difference in one or more of the factors that control soil genesis. The experienced mapper has learned to look for these places and use knowledge of soil genesis to improve the accuracy and efficiency of the mapping (4).

The resulting map unit carries the same name as a taxon. However, it is important to differentiate the map unit and taxon. Although identified by the same name, they are not, in fact, the same. The geographic attributes of spatial distribution (including size and shape), slope, and slope orientation are not taxonomic criteria but are primary attributes of map units.

The taxon concept is also used in making soil interpretations in the soil survey report. The interpretive tables are designed as if the map units were pure or uniform bodies of soil representative of the taxon concept for which the unit is named. Although the soil surveyor attempts to delineate a map unit composed predominantly of the soil taxon indicated, the map unit contains attributes beyond the differentiae required for the taxon as well as inclusions of other soils not qualifying for the taxon named. Perhaps soil scientists have not done a good enough job of informing soil-survey users that some of these interpretive tables are based on the taxonomic concept and not on the actual map unit. This distinction remains a troublesome point for many soil-survey users. It is imperative, then, that the composition of map units be understood if one is to use soil-survey information effectively. Recently, some interpretations have been presented for both the soil mapping unit and the soil taxon.

Components of Map Units

Since the beginning of soil surveys, soil scientists have recognized the heterogeneity of their map units. Soil map units do contain inclusions of soils (both similar and dissimilar) other than the kind that provides the map-unit name. The extent and diversity of the inclusions vary and are related to the scale of mapping, the complexity of the soil pattern, and the skill and diligence of the soil surveyor (6). The soil scientist must recognize this fact and describe the nature and extent of the inclusions in the map-unit descriptions to the best available knowledge.

Recent studies (3, 6-9) have indicated to soil scientists that their map-unit delineations contain more inclusions of both similar and dissimilar soils than previously suspected (although many of these inclusions do not alter the delineation interpretation). This should not limit the usefulness of the soil survey as long as the character of the soil inclusions and their composition are identified and described. Too often, however, the users of soil surveys believe that the map units are taxonomically pure or that, to be useful, they should be taxonomically pure. Taxonomic purity of map units is not the primary objective of the soil surveyor in making soil surveys and should not be construed as the sole test of their usefulness (6). In most areas, taxonomically pure map units would be possible only on maps of very large scale, which would then have such complex patterns that they would not be useful.

During the last two decades, the definitions of soil series have changed from a basis of a taxon defined loosely around a central concept to that of narrower units defined in terms of class limits or ranges in properties. As a result, the concept of similar soils was introduced. Thus, the allowable map-unit heterogeneity for map units named for a single taxon has increased from the 15 percent inclusion tolerance permitted in the 1951 Soil Survey Manual (4) to the more than 50 percent inclusions of similar soils allowed in the 1967 soils memorandum 66. The 1975 Soil Taxonomy (5) permits a map unit to include other strongly contrasting soil series to a maximum of 10 percent for a single series and, if the soil pattern is too complex to be represented at the scale of the map, combinations of strongly contrasting series to a maximum of 15 percent. These changes signify not a reduction in quality control of soil surveys but an acknowledgment of the variability that has been there all along. Some of this heterogeneity has resulted from the introduction of narrower definitions of soil taxa.

One result of the use of narrower definitions of soil taxa has been a fragmentation of soil areas delineated by using the same standards and scale as those delineated earlier. These fragmented soil bodies on the landscape now become taxonomic inclusions in the map units delineated before the taxonomic refinement. These narrower limits of taxonomic criteria do not usually detract significantly from the interpretive value of the map unit although, as Cline (6) points out, such inclusions illustrate once again the difference between units of classification as concepts and units of mapping as real soils.

When contrasting inclusions occur with such frequency that the mapper has difficulty separating them on the landscape, the resulting map unit is identified as a complex of more than one series. Where such complexes contain contrasting series, interpretations for the behavior of the map unit become difficult. Regardless of the amount and type of inclusions, the soil surveyor has the responsibility to describe the map unit as accurately as possible to reflect its divergence from a taxonomically pure unit.

Aside from the inclusions that are recognized to be a result of compromises to scale, correlation, cost, and complexity of the soil pattern, there are also unknown inclusions that result from mapping techniques and unavoidable inclusions of other taxa in the map unit. These unavoidable inclusions are the price we pay for the technique employed in making soil surveys, namely, reading the landscape with its characteristic soil association. Cline has noted that, although such a technique makes soil mapping reasonably accurate and "affordably feasible", some error is unavoidable because (a) the predictive value of landscapes is not perfect, (b) the sampling intensity is inadequate to verify the presence of all soil bodies that may exist, and (c) the sampling tends to be biased toward the most prominent soils and landscape features.

Quantification of Mapping Inclusions

Because soil scientists are aware of inclusions and the limitations of mapping techniques to accommodate all components of map units, studies have been designed to determine quantitatively the composition of map units. These studies have shown that the amounts of inclusions in map units differ enormously among surveys. They also show, however, that many inclusions do not alter the interpretations of the map unit even when taxonomic criteria place those inclusions outside the range of the series identified in the map-unit name.

By using transects, grid-sampling procedures, and other techniques, soil scientists today are quantifying the composition of map units. The objective of these analyses is to obtain estimates of the composition of soil units so that it will be possible to say, for example, that with 90 percent assurance, soil A makes up 60-80 percent of a given delineation of a map unit (10). Or one may prefer to express the variability of this map unit in this way: At the 90 percent probability level, soil A makes up 70 ± 10 percent of the given map-unit delineation. As Arnold points out, this is a simple way to inform soil-survey users that, if we continued to sample areas of the map unit again and again, we believe we would obtain a range in the composition of the map unit that includes the true percentage of soil A. Studies of map-unit composition have increased tremendously in the past 10-15 years (3, 6-9).

Typical of such studies is that of Wilding and others (9), who evaluated the variation of soil morphological properties within 24 delineations of six map units in three counties in west-central Ohio. Ten observations within each delineation were made randomly over a 25-hm^2 (10-acre) tract to determine the character and magnitude of map-unit inclusions. Inclusions occurred within all areas studied and were due primarily to ranges of the properties of solum thickness and drainage that were beyond the class limits of the dominant soil taxon. When all forms of inclusions were taken together (eight measured properties), none of the map units (average of 3 delineations) contained less than 57 percent and none of the 24 individual delineations had less than 30 percent inclusions. At all 240 locations, the soils had been classified in the correct subgroup 83 percent of the time; soil series, 42 percent; and soil type, 39 percent. Parent material had been mapped accurately 88 percent of the time; erosion, 94 percent; pH, 70 percent; solum thickness, 63 percent; and drainage class, 65 percent. Once again, despite the high percentage of inclusions caused by ranges of certain soil properties beyond the class limits of the dominant soil taxon, all but 3 of the 24 mapping delineations were well delineated for interpretations of soil behavior or use.

In contrast to the study of Wilding and others, a similar assessment of map-unit composition on the loess-mantled plains of Nebraska showed that 72 percent of the profiles sampled were members of the series identified in the map-unit name (6).

In summarizing a number of studies to quantify the composition of map-unit delineations, Cline (6) concluded that the delineations had been mapped about as well as could have been expected, considering the technique used, and were adequate for interpretations. Many of the inclusions did not contrast enough to detract significantly from the interpretive value of the map units. It is this situation that led to the recognition of "similar" and "dissimilar" soils in the 1967 soils memorandum 66. Even for highly contrasting or dissimilar soils, as Cline points out, it is important to distinguish between those soils that impose more and those that impose fewer restrictions on soil performance under various uses. Thus, there are both "limiting" and "nonlimiting" dissimilar soils that occur as inclusions. Limiting dissimilar soils are the ones that soil mappers are justified in spending much time and effort to exclude from map units (6).

It is again important to emphasize that taxonomic purity of map units is not a proper measure of the quality or precision of a soil survey. As Cline has stated, the quality of a soil survey should be measured in terms of the amount and accuracy of the information it provides as a basis for judgments about soil potentials and behavior for land use. A map unit may have only 40 percent taxonomic purity or classification accuracy but have 90 percent interpretive accuracy. If one uses the soil survey with the understanding that the interpretive tables are based on the predominant taxon present in the map unit, the objective of the soil survey will have been realized. The interpretive value of soil maps has always been considered as a regional or area evaluation tool. Their use was never intended to be a substitute for on-site evaluations or as a tool precise enough for site-specific interpretations.

SOIL VARIABILITY AND IMPLICATIONS ON USE

Variability: Nature's Ubiquitous Attribute

The soil scientist is by necessity a practitioner of an observational science. Very early in the soil scientist's attempts to characterize the soil and delineate its spatial distribution, he or she is faced with one of nature's most ubiquitous attributes—variability or the natural scatter and range of the population of soils and soil properties. The 1951 Soil Survey Manual (4) reminded the soil scientist that "the variation in nature is fixed; failure to recognize it in no way reduces its magnitude".

The objective of the soil survey is to delineate the landscape into soil units that contain less-variable soil conditions than does the total population of soils. The utility of both the taxonomic system used to classify soils and the resulting soil map depends on the precision of the statements that can be made about the behavior of the delineated units versus that of the area as a whole (11). However, if the magnitude of the variability within these delineated units is not known, the precision of the statements that can be made about them is compromised.

Thus, soil scientists, geologists, soil engineers, and other earth scientists are constantly faced with the problem of determining the confidence limits of their data. How many samples are required to obtain a specified confidence interval in estimating the mean of the entire population? And what are the variability indexes and confidence limits of different properties measured from the same number of samples? The soil scientist cannot speak with equal degrees of confidence about soil pH and clay content, even though both were measured from the same set of samples. Likewise, the soil engineer must recognize that moisture-density relationships and shear-strength measurements do not have equal degrees of variability and, therefore, do not have similar confidence limits when measured from the same sample.

Measuring Soil Variability and Confidence Limits

There are numerous studies (3, 9, 11-13) of the variation of soil properties over distance, but most of them have relied on analysis of variance, according to Campbell (13). It is Campbell's contention that, despite the variety of sampling plans used in these studies, these methods do not permit concise and complete description of changes over distance, and he has therefore suggested and tested another approach to the analysis of soil variability. This approach uses a portion of regionalized variable theory, which encompasses a body of statistical theory tailored for the analysis of the spatial variation of continuous geographic distributions, and centers on the premise that, although the precise nature of the variation of a regionalized soil property (variable) is too complex for complete description, the average rate of change over distance can be estimated by the statistical parameter of semivariance.

The intensive sampling strategy required for this technique is not practical for routine use by soil surveyors. Campbell, however, maintains that it may be possible to obtain rough estimates of the relative degrees of spatial variability without sampling each and every soil body we wish to study.

The study of Wilding and Drees (11) is typical of those using the coefficient of variability (CV) to measure the magnitude of soil map-unit variability. These workers used their own data plus data from the literature to determine CVs for selected morphological, physical, and chemical properties within map units. The CVs for most properties ranged from 25 to 35 percent.

Wilding and Drees also addressed the question of variability and the number of observations necessary to estimate the mean within specific limits at a 95 percent confidence interval. In other words, how many samples are necessary to achieve an accuracy of estimating the mean within ±10 percent compared with those necessary for an accuracy of ±20 percent (at the same degree of variability and confidence interval)? For the evaluated data, the number of observations required to achieve an accuracy of ±10 percent is four times that for ±20 percent at the same CV. These data indicate that, to increase the accuracy of estimating the true mean of the soil population, we must increase our sampling or number of observations exponentially. Figure 1 illustrates the relationship between the number of observations necessary to estimate the population mean within specified limits and the CV.

Figures 2-4 illustrate the variability, as measured by the CV, for soil morphological, physical, and chemical properties as determined from the data analyzed by Wilding and Drees. These evaluations of characterization data indicate that we, as interpreters of the data, cannot speak with the same degree of certainty about the confidence limits of soil pH or of Atterberg limits as about depth to mottling and solum thickness. The first two properties are less variable than the latter two (11). Therefore, the degree of confidence and accuracy of our statements about the pH of a soil map unit is much higher than the accuracy we can express about the mean solum thickness. For the property of solum thickness, we may need to observe three to four times as many profiles as would be necessary to establish the same degree of confidence or accuracy for the properties of mean total silt content or of pH. Table 1 presents a ranking of the variability of the soil properties analyzed by Wilding and Drees that shows the number of soil profiles necessary to estimate the mean of the population within similar confidence limits.

Properties that exhibit CVs of more than 30 percent require so many observations or measurements to obtain an accuracy of ±10 percent that sampling may be impractical. But this situation does not relieve the investigator from the obligations of knowing and describing the basic variability and components of the map unit.

Most sampling procedures used in making soil surveys, engineering soil maps, and other soil measurements are never subjected to statistical evaluation to determine the soil-property variation and its central tendency. Samples are often obtained, properties measured, the data cranked through various equations, and interpretations made as if all measured properties possessed the same degree of variation and confidence limits. As shown in Table 1, this assumption is not valid.

TRANSMITTING SOIL INFORMATION THROUGH MAPS

Basis for Predicting Soil Behavior from Soil Surveys

The objective of the soil scientist, geologist, or other earth scientist in making a map is to provide a spatial classification that transmits information about features at or near the earth's surface for a defined purpose. As Varnes (14) points out, this transmission is effective only if the mapmaker, the map, and the map user are so coordinated that the maker's concept is transferred to the user's mind without significant alteration. The success of transmitting information contained in soil or geologic maps to fit the needs of civil engineers (or any other type of user) depends on the accuracy and reliability that are required, how closely the properties of interest covary with the mapped boundaries, and how heterogeneous the soil or geologic units are with respect to these properties.

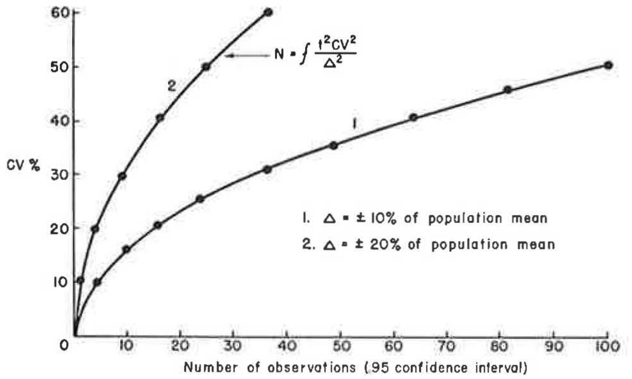
Predictability of Soil Behavior

Soil maps are used largely as a basis for predicting the behavior of soils. The confidence of the prediction from the map is a function of the variance of the soil property or properties concerned.

The method used by soil scientists to derive predictability of soil behavior for soil maps prepared from sample data is to correlate the data with a soil classification of the area. Prediction for any point, therefore, is based on data from the map unit to which the point belongs (2). The basic premise of this technique is that the variance in the map unit is less than the variance in the population of soils in the area as a whole; hence, the confidence interval for prediction should be narrower.

The map user, however, wants to know about individual soil properties or the suitability of the soil map unit or both for a specified use. A soil map provides a definitive partitioning of the landscape into map units, within which the desired information and interpretations of soil behavior are indexed by virtue of their location (2). As is described above, however, the confidence limits of the information contained within the partitioned classes or map units vary with the parameter of interest and the heterogeneity of the soil.

Figure 1. Relationship between number of observations necessary to estimate the mean within specific limits at a 95 percent confidence level and the CV.



Proper Use of Soil Maps

To use a soil map properly, the user should be aware of how soil landscapes are sampled by the soil scientist and how inferences derived from such observations are extrapolated to produce the delineations that result in the map. The user should also be aware of the composition of the map units with respect to inclusions, the relationship of taxonomic heterogeneity to interpretive accuracy, the different degrees of variability of soil properties, and the confidence limits of interpretations of soil behavior. The credibility of a map is no better than the confidence limits of the statements that can be made about the behavior of the soil map units it delineates.

But maps too often convey greater confidence than is warranted. Varnes (14) points out that a map has great power to persuade, a power that has been termed "carto-

Figure 2. Magnitude of variability of selected morphological properties within map units of a series and a series concept.

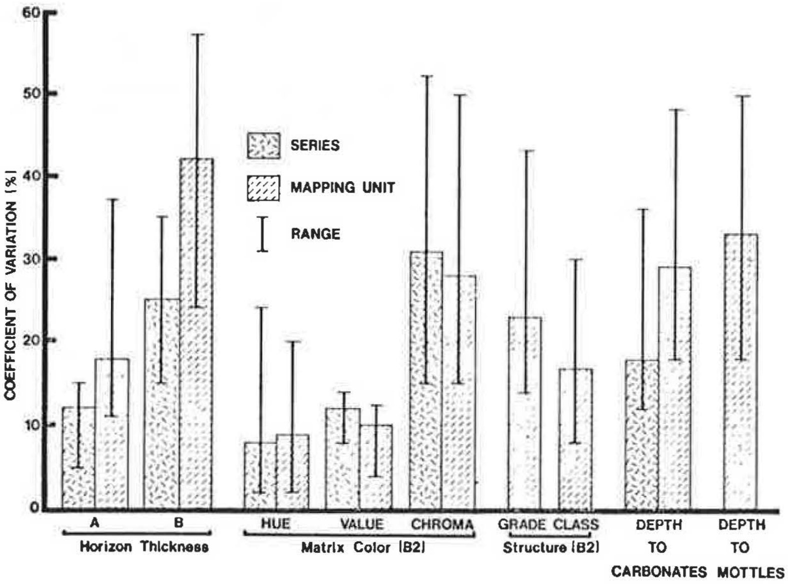
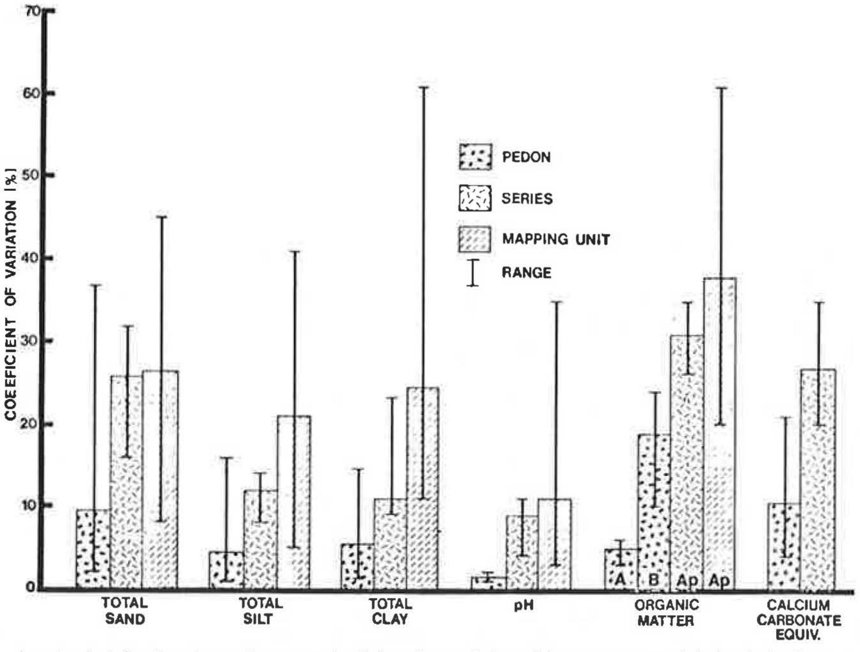
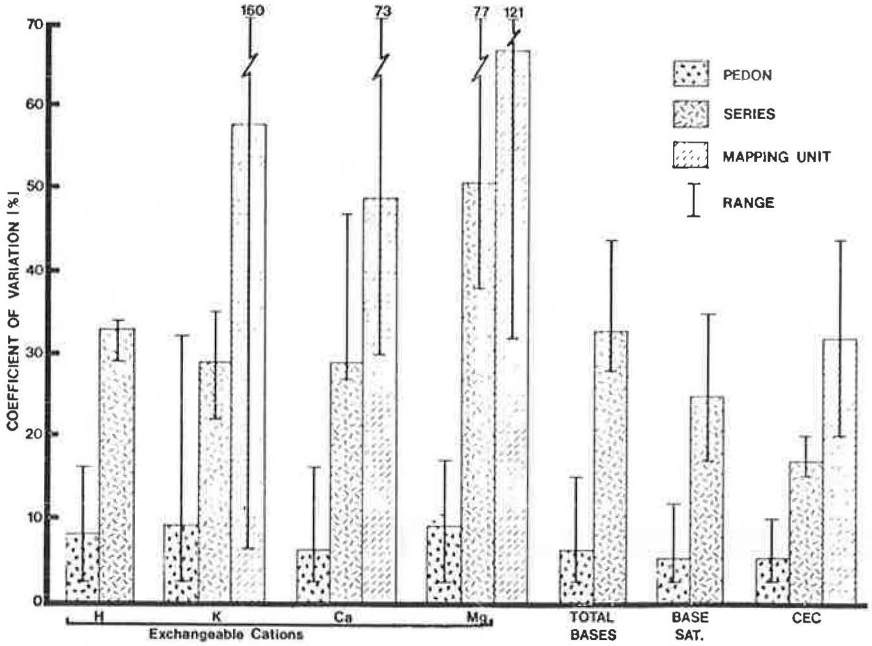


Figure 3. Magnitude of variability for selected physical and chemical properties within map units of a series, a series concept, and a pedon.



A pedon is defined as the smallest area of soil that shows all the soil layers present and their relationships to one another.

Figure 4. Magnitude of variability of selected chemical properties, including exchangeable cations, within map units of a series, a series concept, and a pedon.



A pedon is defined as the smallest area of soil that shows all the soil layers present and their relationships to one another.

Table 1. Relative ranking of variability of soil properties.

Variability of Property	Number of Profiles Needed	Property
Least	>10	Soil color (hue and value)
		Soil pH
		Thickness of A-horizon
		Total silt content
		Plasticity limit
Moderate	>10 to 35	Total sand content
		Total clay content
		Cation exchange capacity
		Base saturation
		Soil structure (grade and class)
		Liquid limit
		Depth to minimum pH
		Calcium carbonate equivalent
Most	>35	B2 horizon and solum thickness
		Soil color (chroma)
		Depth to mottling
		Depth of leaching (carbonates)
		Exchangeable hydrogen, calcium, magnesium, and potassium
		Fine clay content
		Organic matter content
		Plasticity index

hypnosis". Because most users of a map cannot question its content deeply without direct knowledge of the area and because they naturally tend to believe that some information is better than none, the mapmaker should provide a clear and concise statement of how the map was derived.

The credibility of both the soil map and the interpreter are often at stake. Facts cannot be generated from inferences alone. As map producers, soil scientists, geologists, and other earth scientists must not only evaluate the confidence limits of their products but also clearly relay those confidence limits to the potential user. This is especially critical if the user is unaware of the technique used to generate the map and the degree of variability and heterogeneity within the map units. Too often, the engineer who uses soil maps has not understood their intent, potential uses, and confidence limits because the soil scientist has not done an adequate job in conveying these concepts.

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Physical Environment Report: A Geotechnical Aid for Planners

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Since 1976, the Soil Mechanics Bureau of the New York State Department of Transportation has produced reports that delineate information on the physical base of a potential transportation corridor or project. These reports have their origin in the traditional engineering soil map. The transportation planner must identify potential changes in the physical base of an area that could result from a transportation improvement and determine how these changes may affect the environment. The reports present physical-base data on geology, soils, groundwater, and surface water in map form and include an explanation of the mapped units in an explanatory legend. Information contained in the reports includes topography, slopes, terrain units, bedrock, aquifers, erodibility, runoff, floodplain and watershed delineation, and stream-classification data. A brief description of the use of the mapped information is included, along with a listing of references and data sources. This paper briefly describes the data-collection and presentation procedures and the cautionary statements and uses made of the reports.

The Soil Mechanics Bureau of the New York State Department of Transportation (NYSDOT) has for many years provided department planners and designers with reports delineating soil and surficial geologic conditions on a reconnaissance level (1, 2). In the mid-1970s, departmental regional planning engineers began requesting additional information on water-soil interactions such as runoff and erosion potential. At this time, bureau personnel were studying a physical inventory—termed a physical environment report—prepared for the Saskatoon, Canada, area (3) that contained many concepts that could be included in an expanded reconnaissance-level report.

A study showed that an inventory limited to factors within the basic terrain-reconnaissance expertise of the bureau could give planners information on topography, geology, soil type, internal drainage, and soil erodibility. Other easily acquired information such as precipitation data, floodplain delineations, stream classification, and widlife food-and-cover criteria based on soil wetness could also be included. This type of inventory information could alleviate the problems of regional planning personnel attempting to provide physical-base data from often inadequate sources or without the necessary interpretations of source data.

INVENTORY DATA BASE

Because more physical-base information would be collected and interpreted for the physical environment reports than for the previous terrain-reconnaissance reports, a review of accessible source material was made. Terrain reconnaissance as practiced in New York relies heavily on the soil surveys produced by the Soil Conservation Service (SCS), U.S. Department of Agriculture. SCS soil mapping units were converted to NYSDOT terrain units (which are based on landform, mode of deposition, and parent material). Because of the ready availability of soil survey data and the bureau's experience in its use, this information was retained as the basis for interpretation into surficial geologic (terrain) units. In addition, information contained in the soil survey on slope, erodibility, runoff, wetness and ponding, and habitat elements for wetlands wildlife was extracted, evaluated, and interpreted. Supplementary references or information sources to which the report user may go for more detailed information on uses and interpretation of the soil survey information were found; these range from the Soil Survey Manual (4) to papers from various technical journals.

Bedrock information was obtained from the New York State Geological Map (5); groundwater bulletins, the Geological Survey, U.S. Department of the Interior (USGS); and New York State Museum and Science Service publications. Information on aquifers, both surficial and bedrock, was obtained from the same sources.

Climatic data were obtained from the monthly and annual summaries for New York reporting stations prepared by the National Weather Service, U.S. Department of Commerce. Floodplain, wetland, and stream data were acquired from the New York State Department