Lecture Notes & Reference

Methodology for Soil Resource Inventories
2nd Revised Version

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Introduction to these notes

Soil survey, or more properly, **soil resource inventory**, is the process of determining the pattern of the soil cover, characterizing it, and presenting it in understandable and interpretable form to various consumers.

These notes are intended for students who wish to learn the concepts and methods of soil survey. They are meant to be used with a set of practical exercises that make the concepts more concrete. The only specific prerequisites for understanding this material are (1) an introduction to soil genesis, specifically the concept of soil forming factors and processes, and (2) a general background in earth science, remote sensing, cartography, statistics, and computer handling is also required.

The notes are somewhat uneven, largely because of lack of time to put them in consistent form. Some topics are covered in greater depth than others, and in the actual lectures, there is not enough time to teach some material to the depth with which it is presented here. The extra material has been retained as a reference for those who need a deeper appreciation of these topics, e.g. for a personal study topic or as a starting point for an MSc project.

A detailed bibliography is presented at the end of the notes. Several texts and monographs by British authors were particularly helpful [1, 24, 61]. For the current 'state of the art' in America I make extensive reference to their official publications:[48-51] as well as revisions to these available on the Internet.

I have collected many **Internet links** related to soil survey at:

> http://www.itc.nl/~rossiter/research/rsrch_ss.html

Here you can find the most current versions of these lecture notes as a PDF file, as well as for other primary documents such as the Soil Survey Manual [48], Soil Taxonomy [52, 53], World Reference Base for Soil Classification [8, 23, 30].

Contents

1 What is a soil survey?

In this section I define 'soil survey', explain why it is important, and introduce some important concepts and definitions in soil survey. We will define 'soil survey' in detail below; here we simply present the definition of Dent & Young [24]:

> "The practical purpose of soil survey is to enable **more numerous, more accurate and more useful predictions** [of land performance] **to be made for specific purposes** than could have been made otherwise [i.e., in the absence of location-specific information about soils].

This emphasizes that soil survey is **utilitarian**, in other words, the soil is mapped for one or more purposes, not as an object of scientific study. This implies, first, that soil survey should be **demand-driven**, and that methods and products can be specified according to demand and budget. Secondly, we can use **objective criteria** to see if it has met certain specifications. The study of soil for its own sake, as a natural object of interest, is worthwhile and extremely interesting, and if society as a whole or enthusiasts will support it, desirable. However, the kind of soil survey we present in this course must serve society or private interests directly, i.e. **soil survey must be a cost-effective way of improving the overall wealth or well-being of society** or some segment thereof (e.g., individual landowner or land user).

We can from the first separate **two kinds of soil survey**:

1. **Utilitarian**, to answer specific questions about the response of land to land use

2. **Scientific**, to understand the soil as a natural body in the landscape

As it turns out, **in many situations a scientific survey is the most efficient way to obtain a utilitarian survey**. In other words, it is difficult to map the distribution of specific soil properties without understanding the scientific basis of soil-landscape relations.

Remember, **someone is paying for the soil survey**, either society as a whole at some level (the national, regional or local taxpayer), a specific project, or a private landowner or land user. In any case **the soil survey must return the investment**.

1.1 A consumer's view of soil surveys

Soil surveyors must deliver a high-quality product that is useful to one or more groups of **decision-makers**. Most questions about survey methodology can ultimately be solved by fitting the survey method to the decision-maker's needs and budget.

1.1.1 Soil survey consumers

The information **consumer** is a person or organization which needs to know something about soil properties, as outlined in the previous section. For the soil resource, these consumers include:

- **Land managers**: farmers, ranchers, foresters, plantation managers… This group decides what to do with each land area, i.e. what to use it for, and under what management system.

- **Advisors to land managers**: extensionists. This group advises land managers.

- **Service industries related to land use**: e.g. agricultural credit agencies, banks, investment groups. This group facilitates land use and needs to know if their investment will be productive.

- **Land-user planners**: rural, suburban, peri-urban, urban. This group prohibits, advises, or facilitates certain kinds of land use in different areas.

- **Regulatory agencies**: a sub-group of land-use planners, but with a specific legal authority to regulate land use. Example: in the Netherlands, the amount of animal manures that can be applied to a hectare of land is determined by the soil type; the purpose of this regulation is to avoid ground-water pollution.

- **Taxation authorities**: in some countries, land is taxed on its productive potential. The outstanding example is Germany, following the 1934 law designed to insure fair land valuation for taxation and fair compensation for land reallocation.

- **Environmental managers** who use the soil as an element of landscape ecology.

- **Researchers** on the land's response to various land uses and management strategies: e.g. agricultural experimentalists; they expect that different soil units respond differently to management

- **Researchers** on the land's contribution to various natural and human processes: hydrologists, geographers

In each case, the consumer will only use a soil survey if it **increases** their **'productivity'**. So, we can judge the soil survey from a consumer's point of view:

1. How **accurately & precisely** does it answer the consumer's questions?

2. How much **value is added** by correct decisions vs. incorrect ones?

1.1.2 Questions that a soil survey can answer

What kind of information might decision-makers need? Beckett & Burrough [4] present the following classification of questions that could be answered by soil survey [the questions about spatial patterns are my additions] :

1. **<u>Summarizing over an entire study area</u>**
   (a) What **classes of soil** are present in the area?
   (b) In what **proportion** do these occur?
   (c) What proportion of the area is occupied by soils with **specified properties**?

Note that this first group of questions only require a statistically-sound sampling procedure (point or area), and no map. The only interest in these questions would be for a national inventory.

For most decision-making we also want to know the **geographical distribution** of soils, i.e. they must be shown on a **map**. With a map we can answer more questions:

2. **<u>At a given site</u>** (a small area of interest)
   (a) What is the **soil class** at a **particular site**?
   (b) What are the **soil properties** at a site?
   (c) What is the **spatial pattern** of **soil classes** at or around a site?
   (d) What is the **spatial pattern** of **soil properties** at or around a site?

The above group of questions should be asked by land managers who already own or manage specific areas, and by planners who already have identified specific areas whose use or management must be planned.

3. **Locating areas of interest**

(a) **Where** can soil of a particular **class** be found?
(b) **Where** can soil with **specified properties** be found?
(c) **Where** can a specific **spatial pattern** of soil properties be found?

The above group of questions should be asked by planners or land users looking for land on which to implement specific land uses. It could be land already owned, managed or controlled, or land that is to be acquired, managed or controlled.

The last two groups of questions require that we cover the area of interest with **predictions** about the soil cover, so that at any site (directly sampled or not) we can answer these questions. In other words, we must make a **map** of the soil cover to answer these questions.

Some interesting points about these questions

1. **Classes vs. properties**: 'Classes' are categories of a pre-defined classification system or recognized during the survey as natural landscape elements; 'properties' are measurable Land Characteristics, e.g. soluble salts, or inferred Land Qualities, e.g. toxicity to a specific plant variety.

2. **Land evaluation**: For 'properties' in the above definitions, substitute 'combinations of Land Characteristics or Land Qualities that are necessary for the successful and sustained use of the land under a defined Land Utilization Type' and you have transformed the question into the basic Land Evaluation questions.

3. **Implied scale** of these questions: We will discuss map scale and mapping intensity in detail later. Here we should notice that the concepts of 'site' and 'area' implies a scale of interest, and that these questions change their meaning depending on this implied scale. An example of a detailed scale (i.e. small-area 'site'): Sahelian millet farmers who plant according to small differences in micro-relief and organic matter content. An example of a general scale (i.e. large-area 'site'): A national public-works authority planning the priority of drainage or irrigation schemes, where the 'site' is the entire area affected.

4. **Spatial patterns**: Some land uses require a specific spatial pattern of different soil types at a specific ground scale. Sometimes it is not enough to know the proportion of soils at a 'site' or in an area, but also the spatial pattern in which they occur. Example: 10% wet spots (limiting spring planting) vs. 10% contiguous wet areas which can be ignored.

Related questions

1. How **reliable** are these statements? To what degree can the decision maker rely on them? This requires either a quantitative, usually probabilistic, or qualitative accuracy assessment with respect to the questions.

2. How **easy** is it to determine this information? Are the legend and report **understandable** by the consumer? Another way to put this is: **Are the user's questions answered directly**? or must s/he **interpret** the survey?

A technical (but important) **detail: what is a 'point'**?

Mathematically, a point has no dimensions and is infinitely small. Some geographic 'points' fit this definition, e.g. points defined by reference to a grid or geographic coordinate system. Actually, even these are not true mathematical points, because locating them in the field always involves some uncertainty; so these 'points' are actually small areas. We can still use the word 'point' for convenience; and in fact in a vector GIS these are represented as mathematical points (a single set of coordinates).

Now, for soils there is always an *area* (2-dimensional) associated with the concept of a 'point'; so in fact the word 'site' or 'sample site' or 'site of interest' would be better. Here the object of interest itself (the soil or land) has some area; we never study or use a true 'point' but some defined area.

Webster & Oliver [61, p. 29], following the accepted usage in geostatistics, use the word **support** to refer to the **dimensions (area or volume) of the 'individual' that is sampled**, i.e. its size, shape and orientation.

> For example, measurements of the surface reflectance of the soil, using a reflectometer with a known field of view, from a known height, will represent a known area; this is the sample 'point'.

So, we can still use the word 'point', but always specifying its support. For the soil survey consumer, a 'point' is some small area of interest; for the producer, it is the support of the sample that is centered at a mathematical point.

1.2 Types of soil maps

Most surveys produce maps showing the geographical distribution of soil classes or properties. These maps are of several types. The 'area-class polygon' map is the most common in soil survey, but the others can be better solutions in some cases.

1. **Point** soil maps: Maps where the **actual sample points** are shown, along with their **soil class** or one or more **properties**. These have the advantage of being direct representations of what was actually sampled. Not all the area is covered. No model of spatial variability is implied.

2. **Area-class polygon** soil maps: the survey area is **divided into polygons** by **precise boundary lines**, each polygon being labeled with a **class name**, and each class in turn being described in a **legend**. Almost all familiar soil survey maps are of this type, and can easily be represented by the **vector GIS model**. Conceptually, these maps conform to the **discrete model of spatial variation** (DMSV) [34]: the variation across the landscape can be partitioned by sharp boundaries in to relatively homogeneous areas.

   This imposes a hierarchical division of the mapped area into ***m*** classes, and then into individual delineations. Each delineation belongs to exactly one legend class.

<u>Total survey area</u> **Class 1** Delineation 1.1 Delineation 1.2 … Delineation *1.n*$_1$ **Class 2** Delineation 2.1 Delineation 2.2 … Delineation *2.n*$_2$ ... **Class *m*** Delineation m.1 Delineation m.2 … Delineation *m.n*$_m$

(Another name that has been used for this kind of map is a 'chloropleth' soil map [13]; however this use of the term 'chloropleth' does not agree with accepted usage in cartography [45], where it means a map which uses graded tones or colors to represent a statistical surface, with sharp boundaries at the limits of sampling polygons. A classic 'chloropleth' map in this accepted sense is the results of a census, e.g. population density in census areas. It could also be used for single soil properties, e.g. classes of lime requirement on each farmer's field.)

There are several **variants** of area-class soil maps, e.g. with different kinds of boundary lines; overprinted with spot and line symbols, etc.

3. **Continuous-field** maps made by **interpolation**, commonly presented by **isolines** or on a fine **grid** (**'raster' GIS model**). These maps show the **inferred '**continuous' distribution of a **soil property**. They are made by interpolation from point observations. With some methods of interpolation, both the property value and variance can be shown on separate maps. Conceptually, these maps conform to the **continuous model of spatial** var**iation** (CMSV) [34]: there are no sharp boundaries, all variation across the landscape is considered to be continuous.

4. **Continuous-field** maps made by **direct observation** over the whole field, i.e. there is actually a measurement made at every 'point' (in practice, a small area). These are commonly presented as a grid map ('raster' GIS model). These maps show **measured** 'continuous' distribution of a **soil property**. They conform to the CMSV. They have had very limited use in soil survey to date. Currently there is much interest in this type of map of individual parcels for 'precision farming'. Common (non-soil) examples are height (elevation) and vegetation index. Sensors are satellites, aircraft, or ground traverse.

1.3 What is soil survey?

For the time being, we don't worry about the exact definition of 'soil'; this will be explained later. An intuitive notion of soil as the upper surface of the earth is sufficient to understand this section.

1.3.1 Simple definitions of 'soil survey'

Avery [1, p. 1] gives the most general definition:

> "The general aim of soil surveys is to provide information about the soil of areas of land."

This definition includes any systematic soil investigation, not just mapping, and maps of any type (classes, single-factor etc.). But most authors consider mapping a fundamental part of soil survey, e.g., Eyk [26, p. 92]:

> "The primary purpose of a soil survey is to recognize and identify three-dimensional bodies of soil which have significance for some particular objective, and to plot their geographic distribution on a base map"

This definition emphasizes the objective of the soil survey. Note that the 'geographic distribution' can be shown on a chloropleth map or in other ways, depending on the objectives of the survey.

1.3.2 USDA definition of 'soil survey'

Since the first edition in 1937, the USDA Soil Survey Manual has been widely used and adapted, especially in countries with English as the primary scientific language, as well as Latin America. So, we will often refer to the definitions from the most recent (3^{rd}) edition [48]. They define 'soil survey' as follows:

> "A soil survey **describes the characteristics** of the soils in a given area, **classifies** the soils according to a standard system of classification, **plots the boundaries** of the soils on a map, and makes **predictions** about the behavior of soils. The different uses of the soils and how the response of management affects them are considered [in designing and carrying out the survey]. The information collected in a soil survey helps in the development of land-use plans and evaluates and predicts the effects of land use on the environment." (p. 1)

Again, note the emphasis on the objectives of the survey. Let's look at each of the points in turn:

(1) *Describe* the characteristics of the soils in a given area

Notice that the first point is that the soils themselves are the objects of study, and that their characteristics must be investigated. The object is to describe 'soils', not geology, geomorphology, landforms, land use, etc. It may be that the most efficient way to *map* and *understand* the soils is by reference to geomorphology etc., but in the end a soil survey shows the soil conditions in an area.

(2) *Classify* the soils according to a standard system of classification

The purpose of this step is to correlate the soils in the given area to soils elsewhere, as well as to standardize the mapping within a single survey area. The 'standard' system of classification may be an international, national, or local system.

The main practical purpose of correlation is to allow efficient *technology transfer*, i.e. experiences in one area to be applied to another. Note that in some cases soils with similar properties (and hence, we hope, classification) occur over very wide, even discontinuous, geographic areas, so that experience in one area can, with some local modifications, be applied in other areas with these 'same' soils.

(3) *Plot the boundaries* of the soils on a map

For almost all applications, the different kinds of soils must be separated on a map, i.e., it is the geographical location of each soil that is interesting for the land user. Thus for each location on the map, its soil type is indicated (because it is enclosed in a polygon).

(4) Make *predictions* about the behavior of soils

Soil survey is fundamentally a utilitarian activity. This step can be defined narrowly, using only soils data, in which case it is called soil survey interpretation, or it can be included in the broader activity of land evaluation, which uses other kinds of land characteristics (climate, land use, …).

Note that the predictions may be made by other specialists, not the soil surveyor, or (preferably) by the surveyor and interpretations specialists working together. In any case, the soil survey must record the land characteristics that are necessary to make the prediction.

1.3.3 Dent & Young's definition of 'soil survey'

A similar definition, written in more direct language, is that of Dent & Young [24]. They start with the purpose of soil survey, and then how that objective can be met.

"The practical purpose of soil survey is to enable **more numerous, more accurate and more useful predictions to be made for specific purposes** than could have been made otherwise [i.e., in the absence of location-specific information about soils]. To achieve this purpose, it is necessary to:

1. **determine the pattern** of the soil cover; and to

2. **divide this pattern** into relatively homogeneous units; to

3. **map the distribution** of these units, so enabling the soil properties over any area to be predicted; and to

4. **characterize the mapped units** in such a way that useful statements can be made about their **land use potential** and **response to changes in management**."

Note that the map and legend by themselves are not the aim of the soil survey. Instead, it is the *use* that will be made of these. (Of course, from the pedologist's point of view, the soils themselves are the objects of interest.). Note that Dent & Young do not mention correlation to a *standard* classification system.

Both the SSM and Dent & Young definitions only include area-class maps as the product of soil survey ('plot the boundaries', 'divide this pattern into… units').

1.3.4 My short definition of soil survey

> "Soil survey, or more properly, **soil resource inventory**, is the process of determining the pattern of the soil cover, characterizing it, and presenting it in understandable and interpretable form to various consumers."

1.4 Soil survey as an exercise in landscape stratification

In this section we discuss only **area-class polygon** maps, i.e., maps where the survey space is **divided into polygons** by **precise boundary lines**, each polygon being labeled with a **class name**, and each class in turn being described in a **legend**.

Each point in space falls in exactly one polygon, which has a class label, i.e. **each point is assigned to exactly one legend category**. Thus we have **stratified** the landscape, i.e. divided it into groups. This is the sense of the verb ‘to stratify’ or the adjective ‘stratified’ as used in statistics, e.g. a ‘stratified random sample’ is a random sample which takes a defined proportion of the sample from each class (‘stratum’).

> Actually, points are located with some uncertainty both on the map and in the field. If a sample point falls within the error bound of a boundary line (to be discussed in a later lecture), its assignment to a polygon is ambiguous; for the purpose of prediction it could be assigned to either; for the purpose of map evaluation it is evaluated for both polygons.

The big question is: **did the stratification make any difference?** I.e., could we just as well have considered the entire space as one unit? Or, a less drastic alternative, could we have used less classes, less lines, less line length (i.e., a simplified map, presumably costing less to make) without affecting the utility of the map?

A second question is: **did we find the ‘best’ stratification?** I.e., even if our stratification is effective (previous question), maybe there is a better one.

A final question: **how valuable is the soil survey’s stratification**, compared to those made by other disciplines. Which map is more useful?: soils, landforms, vegetation, land use, ownership, agroclimate…

1.4.1 Objective 1: Stratification for a better soil survey & interpretations

Two points of view: producer & consumer of the soil map

Producer: Did the stratification improve the **homogeneity of the map units**?, i.e. are soils within each map unit more alike than the soils taken as a whole over the entire map?

Consumer: Did the stratification make the **predications** that can be made about the map units more precise?

The **hypothesis**, which is usually correct, is that a ‘good’ producer’s stratification leads to a ‘good’ consumer’s stratification. But, they are evaluated differently: the producer’s by the soil characteristics themselves, and the consumer’s by the soil’s behavior (response to use).

The key idea is that by **stratifying** the landscape we can make more specific predictions to be made within each landscape unit, than if we considered all the soils in a region together.

Hypothesis 1: Soils within each stratum are *more similar to each other*, with respect to properties of interest, than the population take as a whole. In other words, they form a more homogeneous group, different from other groups.

Hypothesis 2: Soils within a stratum are *less variable* that the population of soils taken as a whole.

<u>Obvious, qualitative examples</u>

Prediction of crop growth on highly-contrasting soils:

(1) saline wet soils (saline seeps) vs. well-drained, non-saline terraces: major differences in toxicity to roots

(2) rocky, shallow soils on steep slopes vs. deep, stone-free soils on gentle slopes: major differences in runoff-vs.-infiltration, water retention, & rooting depth

…and many similar examples of extreme contrasts within small distances.

<u>Examples from environmental modeling</u>

Example: groundwater eutrophication (by P) should be more severe on soils with low phosphate sorption capacity; if the map units separated by the stratification of soil survey are more homogeneous with respect to the their P sorption capacity. In fact this is the basis for limits on manure spreading on crop and pasture land in NL.

Counter-example: soil pollution by radioactive fallout (Chernobyl). Probably soil has almost nothing to do with this, it was atmospheric deposition. Maybe in a few tens or hundreds of years, local erosion will have re-arranged the fallout (cf. Cs137 studies of erosion).

1.4.2 Objective 2: Stratify for further sampling

When further sampling is performed, e.g. for environmental modeling, soil degradation studies etc., the map units established by 'conventional' soil survey are almost always the starting point. The hypothesis is that these strata allow more efficient sampling.

Example: in a ground-water pollution study, it would make sense to stratify the sample space according to the soil's leaching potential, and concentrate our effort on those areas where we think pollutants will leach to the ground water. In other areas we could sample much less intensively.

1.4.3 Objective 3: Stratify for experimentation

Map units can form the blocks of randomized block designs in agricultural or other land-use experimentation.

1.4.4 Objective 4: Stratify for the continuous model of spatial variation

Geo-statistical estimation is usually greatly improved by stratification, since it removes a large source of variation. Point observations can be corrected by the expected value in each stratum, then the spatial structure not accounted for by the strata can be seen.

Examples: [54]

1.5 Are soil maps worthwhile? A preview

We will see how to compute the predictive value of soil maps later on. For now, we just present some results to get some idea of how successful soil survey might be. We consider the question: **How well did the survey separate the total variability of the mapped area**? In other words, of the total variability in the soil survey area, how much is removed by the map and classification? Mathematically, this can be measured by the **proportion of variance of a property explained by the map classes**.

The Intraclass Correlation (derived later) was developed by Webster & Oliver [61, pp. 67-70] for this purpose. Intuitively, a value of 1 means that the map explains all the variation in a soil property, a value of 0 means that the map is useless for explaining the variation. The closer to 1 the better, obviously. High values mean that knowing in which map unit a sample is located greatly increases our knowledge about its possible value.

Here is an example table from Webster & Oliver showing the Intraclass Correlation for several properties as predicted by API units in a terrain analysis exercise originally by Beckett & Webster in the mid-1960's:

Soil property	Intraclass correlation (0…1)
clay (%)	0.61
pF in summer	0.66
soil strength in winter (cone index)	0.70
organic matter (%)	0.28
pH	0.33
available K (%)	0.06

These are fairly typical of soil survey, although both the landscape and classification system, as well as the skill of the mapper, have a heavy influence on the results. In general, physical properties are more easily separated than chemical, subsoil more than topsoil (in cultivated areas). Properties that are closely correlated with externally-visible features (e.g. landscape elements mappable on an airphoto) also are easier to separate.

1.6 Kinds of soil surveys

In all cases the aim of soil survey is to show the geographic distribution of soils. But there are important differences in the objective of the survey and, from that, methods. We distinguish:

(1) Special-purpose and general-purpose soil surveys;

(2) Surveys with predominantly simple vs. compound map units ('one-stage' vs. 'two-stage')

1.6.1 Special-purpose and general-purpose soil surveys

(1) Single-characteristic soil surveys

This is the extreme case of the special-purpose survey. A single soil characteristic (or, a few at the same time) are measured and the limits between pre-defined classes of these characteristics are mapped; The map unit limits are directly applicable to a use. A typical example is a map of salinity and a separate map of infiltration rates, both for an irrigation project.

These are ideal candidates for **continuous** maps, see below.

(2) Special-purpose soil surveys

These surveys are designed for a single, well-defined, objective. The classic example is a survey to determine which lands to irrigate in an irrigation project. Another example is conservation-oriented farm planning, where the objective is to assign correct conservation practices to each land area. In contrast to the single-characteristic survey, map units are defined which combine relevant characteristics.

The **advantage** of a special-purpose survey is that we know the properties of interest for the special purpose and can concentrate on mapping these, so that the mapping is more rapid and can be done with less-skilled mappers (i.e., not just trained pedologists). But, we may not record properties that are vital for other uses.

Special-purpose legends: the map units are described by their properties; i.e. there is no mapping legend, only a descriptive legend. Each delineation receives a symbol that directly indicates the mapped properties. Example: '3a-d-1' might mean 'texture class '3', slope class 'a', depth class 'd', erosion class '1'. The legend addresses exactly what the survey is intended to map, and can be directly translated to the objective.

Example: Brazilian system for directly mapping the physical environment.[41]

The **disadvantage** of this kind of survey is that it is **mostly useless for other objectives**. It may be just as cheap to make a general-purpose survey, at least the landscape stratification if not the detailed characterization.

Also, there is a problem defining boundaries when there is no concept of natural soil body. Sometimes it is on a parcel basis: existing units of exploitation are directly classified according to their properties.

(3) General purpose soil surveys

These provide the basis for a variety of interpretations for various kinds of uses, present and future, including some we can't anticipate now.

The **advantage** is that the survey can be re-used for many purposes, assuming that the survey makes a correct stratification of the landscape. In fact, the strata can be re-sampled later for characteristics that weren't measured at first.

The **disadvantage** is that the survey isn't ideal for any purpose; also we may not anticipate future needs. Example: 'general purpose' surveys pre-1970 applied to ground-water contamination studies;

estimations of carbon budget (heavily influenced by management) from maps of soil series. Another disadvantage is *cost*. Some expensive analyses may never be used.

The trend has been towards general-purpose surveys, sponsored on a 'speculative' basis coordinated by a national mapping agency (e.g., in the USA, the Soil Conservation Service has formed a National Cooperative Soil Survey). However many situations with less resources and immediate needs, the special-purpose survey prevails.

Compromise: intensive general-purpose surveys in areas with current or future multiple conflictive uses, extensive special-purpose surveys for areas that will not change land uses, e.g. forest reserves. In fact soil surveys for forestry areas have almost always been at less detailed scales and with less detailed characterizations than surveys for agricultural areas.

Hypotheses of the general-purpose survey

Why do soil scientists believe that the general-purpose survey is usually more cost-effective?

Hypothesis 1: Soils are natural bodies formed by natural & anthropic processes whereby land characteristics co-vary; i.e., not all combinations of land characteristics occur.

Hypothesis 2: The spatial pattern of these natural bodies can be predicted and correlated to **external features** that can be relatively easily mapped over the entire landscape, certainly more easily than by exhaustive sampling. We can predict by combinations of geomorphology, vegetation, current land use, and historical records.

Hypothesis 3: The natural soil bodies are the most effective **information carriers**, because they bring together many land characteristics in a predictable pattern. If a certain soil characteristic or quality is not measured during the survey, it can be done later when a new land use is foreseen, and the **stratification** established by the general-purpose soil survey will make the sampling, testing and prediction **more efficient**.

1.6.2 Predominantly simple vs. compound map units

Surveys can be classified according to whether they attempt to show **simple map units** in the majority of their delineations, or whether they show **compound map units**, i.e. map units with two or more constituents, which are not separated on the map. By 'constituent' we mean 'relatively homogeneous' at some categorical level of detail.

This is partly a matter of scale: large-scale maps tend to show simple map units, and small-scale maps tend to show compound map units. However, at any scale the decision can be made to trade **categorical detail** for **map unit purity**.

'Two-stage' soil maps

Beckett [3] calls maps with mainly compound map units 'two stage maps'. He points out that even if the published map does not delimit homogeneous soil bodies, it can still be useful **if the map user can find the homogeneous soil bodies** in the field or on an airphoto, with the aid of the compound map unit's description in the soil survey report. His proposal was in the context of extensive, small-scale, mapping for land evaluation.

For example: Plate 1 in Dent & Young [24] shows a very intricate soil pattern in a depositional landscape on the East Anglian fens (Britain). In the photo we can easily see the detailed pattern of abandoned estuarian creeks (fine-sandy & silty) and tidal flats (silty clays) that were later covered by a uniform blanket of peat. Since exploitation the peat has shrunk, so that the soil pattern is exposed. This pattern can easily be seen in the field and on the airphoto; however since the field scale of the pattern is on the order of 2 to 5m-wide abandoned creeks, the map scale would have to be 1:2 000 to 1:5 000 to show the soils as simple map units. For most purposes this is impractical, hence the map unit is defined as an complex, and the delineations may be $O(10^4)$ ha instead of $O(10^3)$ m².

1.6.3 Demand-driven vs. supply-driven surveys

This is another way to classify surveys, quite linked to the previous one.

Demand-driven

On-demand, for one or more specific purposes, to 'exploit' the soil resource; explicitly utilitarian; must provide information for a specific set of interpretations; any additional information is superfluous and does not count as a benefit of the survey. We make a map of only the factors that are requested. An example is a soil survey for a development project.

This would be the case in a **land evaluation** exercise where the Land Utilization Types (LUT), their Land Use Requirements (LUR), and the LURs' diagnostic Land Characteristics (LC) are defined first (e.g. by the objectives of the development project), and then data is collected. Here all we need is the diagnostic LCs and we can complete the evaluation.

Supply-driven

We make a basic map, using best scientific practice, of the soil cover. This map tries to provide as clear a picture of soil geography as possible. It is similar in philosophy to a general geologic survey or base map: we expect to use the basic information, from a single survey, for multiple uses, some unforeseen now. We suppose that the stratification will be useful for many interpretations and also serve as the basis for future sampling.

In fact, the 'supply-driven' makes (implicit or explicit) assumptions about the possible uses to which the soil map could be put. There is no other way to decide on the correct scale, legend composition, and survey methods.

2 What do we map in soil survey?

Before discussing soil survey, we must be clear on what is the soil that we map, and how this concept relates to the broader idea of 'land', which itself is often included in our surveys. A practical soil map almost always includes non-soil areas and, even in 'soil' areas, non-soil land characteristics (by any definition of 'soil'). The debate on 'what is soil? 'is interesting in its own right, and has implications for soil survey.

First, we discuss 'land' vs. 'soil'.

2.1 What is 'land'?

The **common-sense** definition: "Solid part of the earth's surface (as opposed to *sea*, *water*, and *air*)" [56].

The neo-Greek term 'Geoderma' (= 'earth skin') is the name of a scientific journal concerned with soil science.

A technical definition of 'land', adapted and expanded from [28]:

> "***Land***: An **area of the earth's surface**, the characteristics of which embrace all reasonably **stable, or predictably cyclic, attributes** of the biosphere vertically above and below this area, including those of:
>
> - the atmosphere;
> - the soil;
> - the underlying geology and associated landforms;
> - the hydrology;
> - the plant populations;
> - the animal populations;
> - the microbiological populations; and
> - the results of past and present human activity,
>
> …to the extent that these attributes exert a significant influence on **present and future uses of the land by humans**."

The idea is that land has a *geographic extent* and is described by *all the characteristics that might influence land use*. It is clear from this definition that 'soil' is only part of 'land'. It is also clear that a land map would be more useful than just a soil map.

2.2 What is ‘soil’?

As seen in the previous definition, ‘soil’ is a component of ‘land’. But, what exactly do we mean by ‘soil’? Not surprisingly, this has caused quite a controversy over the years. First we try to define ‘soil’, then we discuss what we actually map.

<u>Dictionary definition</u> [56]

> “Upper layer of earth in which plants grow, consisting of disintegrated rock usually with admixture of organic remains, mould”.

This definition excludes solid rock and deserts, which are considered to be geological materials only. It excludes earthy materials that can not support plant life, e.g. extremely acid mine spoil.

<u>Simple pedological definition</u> [26, p. 43]

> “The most fundamental and, possibly, the only real difference between soil and other *unconsolidated geological materials* is that, in the case of soil, the *materials have been organized* by natural, non-depositional processes into horizons”.

In this view, soil is a **natural body** of **unconsolidated material** that forms at the earth’s surface by **pedogenetic processes**. This definition excludes fresh sediments and weathered geological material that has not undergone pedogenesis. These areas are mapped, but not as soil, rather as surficial geology. It includes secondary consolidated materials such as petrocalcic horizons, because they formed by pedogenesis.

This definition would seem to exclude earthy materials that have been organized or heavily influenced by human activity.

<u>Another pedological definition</u> [6, §26.1]

> “Soil is the uppermost layer of the earth’s crust, in so far as this layer is or can support plant roots, or in so far this layer has been altered by the action of physical, chemical or biological processes” (my translation).”

The authors add by way of clarification: “Thus, solid rock and the wet, unripe lower parts of loose sediments are not ‘soil’ from the point of view of soil science”.

<u>Definition by its function as an interface</u>

The natural processes of pedogenesis take place at the **interface** between atmosphere, biosphere, lithosphere, hydrosphere, and anthrosphere. In fact, some authors consider **biological activity** as a *sina qua non* of ‘soil’ (as opposed to unconsolidated geological material); others just consider the position as an interface, e.g. [1].

<u>Soil Taxonomy</u> [49] **<u>definition</u>**

> “**Soil** is the collective term used ... for the **natural bodies**, made up of **mineral and organic materials**, that
>
> - cover much of the earth's **surface**,
> - contain living matter and can support vegetation out of doors, and

- have in places been changed by human activity.

"The **upper limit** of soil is air or shallow water.

"Its **horizontal boundaries** are where it grades to deep water or to barren areas of rock or ice.

"The **lower boundary** that separates soil from the not-soil underneath is most difficult to define. Soil consists of the horizons near the earth's surface which, in contrast to the underlying rock material, have been **altered** by the interactions, over time, between climate, relief, parent materials, and living organisms.

"However, soil ... does not need to have discernible horizons, although the presence or absence of horizons and their nature is of extreme importance to its classification. In the few places where the soil contains thin cemented horizons that are impermeable to roots, it is considered to be as deep as the deepest cemented horizon. More commonly, soil grades at its lower boundary to hard rock or to earthy materials virtually **devoid** of animals, roots, or other **marks of biologic activity**. Thus the lower limit of soil is normally the lower limit of biologic activity, which generally coincides with the common rooting depth of native perennial plants.

"If, however, either biological activity or current pedogenic processes extend to depths greater than 200 cm, the lower limit of the soil that we classify is arbitrarily set at 200 cm. For certain soil management purposes, layers deeper than the lower boundary of the soil that we classify must also be described if they affect the content and movement of water and air in the soil of the root zone."

From [50, p.1]; emphasis & punctuation added.

Notes: (1) the requirement to support vegetation out-of-doors means that given sufficient inputs, vegetation could be supported; it does not mean that vegetation must be present. Thus deserts are included, but ice fields are not. (2) The 200 cm limit directly contradicts the statement that immediately follows! Actually, they don't say that it isn't soil below 200cm, just that we don't use any deeper horizons to classify the soil. (3) The definition seems to exclude areas where the natural soil has been heavily influenced by human activity, at least until new 'natural bodies' form.

Some more 'clarification' from the USDA Soil Survey Manual [48, p. 7-8]:

"The 'natural bodies' of this definition include **all genetically related parts of the soil**. A given part, such as a cemented layer, may not contain living matter or be capable of supporting plants. It is, however, still a part of the soil if it is genetically related to the other parts and if the body as a unit contains living matter and is capable of supporting plants.

"The definition includes as soil all natural bodies that contain living matter and are capable of supporting plants even though they do not have genetically differentiated parts. A fresh deposit of alluvium or earthy man-made fill is soil if it can support plants.

"**To be soil, a natural body must contain living matter**. This excludes former soils now buried below the effects of organisms. This is not to say that buried soils may not be characterized by reference to taxonomic classes. It merely means that they are not now members of the collection of natural bodies called soil; they are buried paleosols.

"**Not everything 'capable of supporting plants out-of-doors' is soil**. Bodies of water that support floating plants, such as algae, are not soil, but the sediment below shallow water is soil if it can support bottom-rooting plants such as cattails or reeds. The above-ground parts of plants are also not soil, although they may support parasitic plants. Rock that mainly supports lichens on the surface or plants only in widely spaced cracks is also excluded.

> "**The time transition from not-soil to soil** can be illustrated by recent lava flows in warm regions under heavy and very frequent rainfall. Plants become established very quickly in such climates on the basaltic lava, even through there is very little earthy material. The plants are supported by the porous rock filled with water containing plant nutrients. Organic matter soon accumulates; but, before it does, the dominantly porous broken lava in which plant roots grow is soil."

2.2.1 Major controversies on the definition of 'soil'

In this section we discuss some controversies about the definition of 'soil'. If we make a *soil* map, we must know what properties are considered to be *soil* and which are not. In the next section, we will consider whether to make a pure soil map, or a soil map with some non-soil characteristics. So in fact the definition of soil can include or not some property, and that property can still appear on the 'soil map'.

(1) Is soil climate to be included in the definition of 'soil'?

We know that climate affects soil formation. But, is the climate of the soil to be considered one of its **properties**, and therefore should it be **included in the classification and mapping of soils**?

Yes: says Soil Taxonomy [49]. Soil climate is diagnostic for many land uses and associated with many soil characteristics and processes. The 'soil climate' (internal) is included in the definition of 'soil' even at the highest level of classification (e.g. Aridisols) and below. The moisture & temperature regimes of soils (mean and seasonal) are extremely important in the soil's function. The climate is a characteristic **of the soil**. In practice, we often estimate the soil climate from the air climate, but ideally we would measure soil climate directly.

No: French [2], World Reference Base (**WRB**) [8, 23, 30]. Map the morphology of the soil, in the case a morphology only occurs in some climates, so be it. The concept of 'land' certainly includes climate, but the concept of 'soil' does not. In practice the WRB defines morphological assemblages closely tied to a particular climate, e.g. the 'aridic soil properties'. In the WRB approach, the FAO Agro-ecological Zones [27, 29] methodology is used separately to assess climate.

Definitely the soil climate is necessary for interpretation. But so is the atmospheric climate: for example, dew, frost, air humidity etc. that is not soil climate. These influence even soil interpretations, e.g. workability, let alone agricultural land use interpretations.

Practical consideration: whatever is included must be mappable by the soil surveyor. Soil climate is not directly mappable, but is relatively easy to infer from simple calculations or observations of native vegetation. Soil climate varies much less than atmospheric climate.

(2) Is landform to be included in the definition of 'soil'

We know that landform has a large influence on soil formation and land use, but should we consider landscape position as a *soil* property and indicate it in the legend?

Yes: the landform is useful for interpretations, and the function of soil in the landscape often varies with its landscape position, even if its internal *static* properties are the same. So if we consider the soil as a *dynamic* functional unit in the landscape, we must include its landscape position. In practice, this position helps the mapper and user identify the soil body.

No: keep landform as a separate map, map only the static soil properties.

In practice, many soils show static properties that are also influenced by landscape position, so they are mapped separately anyway. But sometimes not: e.g. occasionally-flooded vs. never-flooded terraces.

(3) How deep can soil be?

The original definition of the **solum** was the topsoil ('A' horizons) + subsoil ('E' and 'B') horizons; where the 'C' horizons were defined as strata with little evidence of pedogenesis. Therefore it was inferred that the C horizons had very little biological activity, including roots. The 'effective soil depth' then was considered the solum thickness. Many studies have now shown that the rooting zone and the zone of biological activity can be very deep and include obvious C horizons, in the morphological sense, in which case the 'effective soil depth' from a functional point of view includes these deeper layers. If the B horizons rest on hard bedrock, the solum thickness is obviously the soil thickness.

There is evidence of biological activity to 10s of meters in some tropical soils. If the ground-water table is very deep, the zone of filtration (vadose zone) is also very deep. In general we exclude from soil zones that have weathered by purely chemical processes; this is very hard to define.

Deep layers can be important for **interpretations**, especially for environmental modeling, whether or not we consider them soil; in this sense they should be mapped in any case.

For all these reasons, there is a movement within soil science to study the deeper strata; this is called 'whole-regolith pedology' [18].

Practical problem: how to map these deep layers? They are often not so related to external properties that we use to aid in soil mapping.

In practice most soil survey organizations set an arbitrary depth for investigation, determined by the effort needed to map to that depth and the value of the interpretations. Additional subsoil investigations can be made in a few sites, to get a general idea of the substrata, whether or not they are considered 'soil'.

(4) Are secondary cemented horizons part of the soil?

Petrocalcic horizons, duripans, ironstone (hardened plinthite), etc. are definitely caused by pedogenetic processes. But they usually stop roots and other biological activity. So should the definition of 'soil' stop at these layers, or should they be included in the 'soil'?

Yes: they were caused by pedogenesis, so are genetically linked with the rest of the soil

No: they are secondary surficial geological materials now, not soil; their only function is as a limit to the soil activity.

Certainly at least their extent, thickness and depth from the surface must be mapped for interpretations.

(5) What about sterile land areas?

In other words, must plants be able to grow on an area of land for it to be considered 'soil'?

For example, highly saline areas, bare rock, coarse sands, mine spoil…

Perhaps this depends on the expense of reclamation, i.e., 'how far' they are from soil.

In any case they must be delineated on the map and characterized to a certain extent.

(6) What about earthy materials formed or heavily influenced by humans?

E.g. dumps, mine spoil, leveled sand dunes, deeply plowed or mixed areas, fill from dredging…

The current thinking in the USA is to **include** these as ‘soil’ as soon as they are exposed to soil-forming processes, or if they can support plants, in practice as soon as they are at or near the earth’s surface. In fact Soil Taxonomy has an active working group on these ‘anthrosols’.

In any case they must be delineated on the map and characterized to a certain extent.

(7) Where does ‘soil’ end and ‘water’ begin?

Or more precisely, ‘lake bottom’ or ‘sea bottom’, i.e. earthy material under water?

Option: soil ends at the high-water mark; this is the most common choice.

Option: soil ends at the low-water mark; so tidal flats and seasonally-flooded areas are also mapped.

Option: soil extends as far as bottom-rooted plants (water lilies, reeds, cat-tails). The roots of these plants respire, so there is microbiological activity in this zone.

Option: soil extends to some arbitrary depth under water, e.g. 2m, regardless of whether plants are rooting there.

2.2.2 What do we actually map in ‘soil’ survey?

Options: land, soil, soil + some land conditions, soil + other surface material, …+ some land conditions; the rest of the map is covered with miscellaneous land areas such as water bodies.

(1) Land conditions

Soil itself; landform; surface conditions (e.g. stones); groundwater & surface water regime; substratum; current land use; climate.

Obviously more useful than just soil

Problem: more difficult

Problem: some boundaries may not coincide; we may get many small map units. This can be avoided to some extent by using physiographic mapping units.

(2) Soil only

Only the soil properties, according to some definition of ‘soil’ (previous §). But this leaves out many important characteristics that influence land use and which are easily seen and mapped by the soil surveyor.

Areas of ‘non-soil’ are delineated but not characterized.

(3) Soil & intimately-associated surface conditions

In practice this is the most common 'soil' map. **Phases** of soil map units include slope, micro-relief form, stoniness… (see later § for list of phases).

(4) Include other surface material

If 'soil' is narrowly defined, this would allow the mapping of human-influenced areas

In any case it allows the mapping of surficial geology that is not soil, e.g. rock outcrops, sand dunes… These have to be characterized to some extent.

(5) GIS 'solution'

Each discipline makes a separate map, these are collated in a GIS (common geo-reference)

Caution: must ensure that **common boundaries are represented only once**; therefore we must establish a **hierarchy** of boundaries, based on their reliability and logical relation.

Solution 1: a joint survey project

Solution 2: agree on major boundaries that everyone will use; fill in database within these boundaries. This fits well with landscape analysis. Each survey could sub-divide these units if necessary, or eliminate unnecessary (from its point of view) boundaries, but the main landscape lines are never drawn twice by different surveys. A geopedological map could be an excellent basis for this.

2.3 The soil continuum & the soil individual

Clearly, soil varies continuously across space. In this section we examine the nature of the variation, and how soil mapping proposes to deal with it.

2.3.1 The natural variation of the soil continuum over the landscape

Since the soil-forming factors vary continuously over the landscape, so do the soils that are thereby formed. We can try to map this directly with the **continuous model** of spatial variation [34], or we can try to divide the continuum with the **discrete model** of spatial variation.

Types of properties: Internal vs. external

Internal properties of the soil: **what we want to map**, from the mapping legend and/or classification system. E.g., the depth and properties of horizons.

External properties: **what we can easily see** in the field or on airphotos. Example: landform, landscape position, slope, vegetation, surface color, surface wetness…

Types of properties: diagnostic, differentiating, accessory, accidental

Diagnostic: must be separated on the map; required by the mapping legend (which may be a classification system). E.g. Horizon thickness, color, pH… These may be easy or hard to determine in the field.

Differentiating: a property used for mapping, often an external property, e.g. slope position in a catena. This must be easy to find in the field and well-correlated with diagnostic properties.

Accessory: are separated on the map because they occur with the differentiating properties. They are usually harder to map directly than the differentiating properties. E.g. A horizon thickness vs. slope position. The ideal situation is when a diagnostic property is well-correlated with a differentiating property, then the mapping is easy.

Accidental: has no relation with what is mapped, its values occur 'by accident'. E.g. surface pH in an active agricultural area is determined by recent land-use history and very poorly correlated with soil type, therefore we wouldn't use it to map soils.

2.3.2 Boundaries

Boundaries between polygons on an area-class map are of several types:

Abrupt vs. gradual

Abrupt: a more-or-less clear line in the landscape (and almost always on the airphoto)

Gradual: a transitional zone. If wide enough (according to its width on the map), it could be mapped separately.

Natural vs. artificial

Natural: from a combination of soil-forming factors, recognized in the landscape. We draw the lines where we recognize significant changes in one or more soil-forming factors. Example: at a scarp between two terraces with similar parent materials but significantly different ages.

Artificial: from an externally-imposed criterion, e.g. classification system. For example, we may try to separate two soil series that differ only in their family particle size class, fine-silty vs. fine-loamy. In a certain coastal plain sediment, there may be a gradual shift from a loamy to a silty sedimentary facies, with a wide transition zone. Any single pedon can be assigned to one of the two series. We try to draw the best boundary based on our borings, but there are no external or differentiating characteristics to help us. On further investigation, these boundaries often turn out to be poorly-placed.

2.3.3 The soil 'individual'?

Obviously, there is no soil 'individual' in the sense of an individual tree or animal.

Knox [38] argues that there is no need for individuals:

> "The emphasis on individuals in soil classification results largely from the idea that a class is an aggregation of individuals. The idea that a class is a range of applicability of a class concept eliminates this unnecessary emphasis".

In this view, we classify our conceptual space (e.g. family particle size classes as a classification of a continuous trivariate space). Yet, there is certainly still a **sampling** (observation) **unit**, which we now discuss.

The Pedon

This concept was introduced with the early approximations to Soil Taxonomy [49] and is now part of the Soil Survey Manual [48, p. 18-19]:

> "The pedon is presented in Soil Taxonomy as a **unit of sampling within a soil**. The limits on the area of a pedon establish rules for deciding whether to consider one or two or more kinds of soil within a small-scale pattern of local lateral variability. **A pedon** is regarded as the **smallest body** of one kind of soil **large enough to represent the nature and arrangement of horizons** and variability in the other properties that are preserved in samples.
>
> "A pedon extends down to the lower limit of a soil. It extends through all genetic horizons and, if the genetic horizons are thin, into the upper part of the underlying material. The pedon includes the rooting zone of most native perennial plants. For purposes of most soil surveys, a **practical lower limit** of the pedon is **bedrock or a depth of about 2 m**, whichever is shallower. A depth of 2 m provides a good sample of major soil horizons, even in thick soil. It includes much of the volume of soil penetrated by plant roots, and it permits reliable observations of soil properties.
>
> "**The surface of a pedon is roughly polygonal and ranges from 1 m² to 10 m² in area**, depending on the nature of the variability in the soil.
>
> 1. Where the cycle of variations is less than 2 m and all horizons are continuous and nearly uniform in thickness, the pedon has an area of approximately 1 m².
>
> 2. Where horizons or other properties are **intermittent** or **cyclic** over an interval of 2 to 7 m, the pedon includes **one-half of the cycle** (1 to 3½ m).
>
> 3. If horizons are cyclic over an **interval greater than 7 m**, each cycle is considered to contain more than one soil.
>
> The range in size, 1 to 10 m², permits consistent classification by different observers where important horizons are cyclic or repeatedly interrupted over short distances." (punctuation, numbering and emphasis mine.)

An important practical consequence of this definition is that the lateral limit of one 'soil individual' is at most 3½m. A good example of the difficulties is shown by Avery [1, Fig. 17].

Polypedon

The pedon, as a 'point' concept, is not useful for mapping. It has two fundamental failings:

1. It has a very **small extent**, so can't show any 'macro' landscape features, most notably local landform (slope, curvature), landscape position, surface stoniness, erosion… which are essentially **area concepts**, whereas the pedon is a 'point' (actually, small area) concept.

2. It does not exhibit any **spatial variability** even of the soil class it is supposed to represent, only the internal variability within a 'point'.

Soil Taxonomy therefore introduced the concept of the **polypedon**:

> "The pedon is considered too small to exhibit more extensive features, such as slope and surface stoniness. The polypedon is presented in Soil Taxonomy as a **unit of classification**, a soil body, **homogeneous at the series level**, and big enough to exhibit all the soil characteristics considered in the description and classification of soils.

> Polypedons link the real bodies of soil in nature to the mental concepts of taxonomic classes"

The need to have a realistic land surface area to map is clear enough. The big controversy comes with the idea that there is usually a contiguous, compact, continuous area within which all pedons classify to the same taxon (e.g. soil series).

The new Soil Survey Manual [48, p. 19-21] largely discounts the concept of polypedon:

> "In practice, the concept of polypedon has been largely ignored and many soil scientists consider a pedon or some undefined body of **more or less similar soil represented by a pedon** large enough to classify [or map]. Polypedons seldom, if ever, serve as the real thing we want to classify [or map] because of the extreme difficulty of finding the boundary of a polypedon on the ground and because of the self contradictory and circular nature of the concept. Soil scientists have classified pedons, regardless of their limited size, by deliberately or unconsciously transferring to the pedon any required extensive properties from the surrounding area of soil.
>
> "… the **point pedon** … combines the **fixed position of a pedon** with consideration of **whatever area is needed** to identify and measure the properties under consideration [36]. This concept, combined with criteria for the scale of lateral variability to be considered within one kind of soil, could establish the pedon as the basic unit of classification and eliminate the need for the polypedon."

<u>Solum & systèmes pédologiques</u>

The French have a different idea of soil individuals, as explained in the Référentiel Pédologique [2]. There is no soil *individual*, only a '1+ dimensional' *sampling unit*:

> **solum**: A vertical face of a profile, preferably to the underlying rock, a few decimeters wide, a few cm thick (just enough to include structure)

The '1+ dimension' refers to the fact that only the *vertical* dimension is fully expressed; the lateral and facing dimensions (into the profile) are not fully sampled.

> (Note that this definition of 'solum' differs from the American definition [47]: "**solum**: A set of horizons that are related through the same cycle of pedogenic processes; the A, E, and B horizons.")

Problem: what about large-scale structures, e.g. relic frost polygons or fragipan polygons that may 1 to 5 m in diameter? Or medium-scale structures such as tonguing of horizons?

Then, the Référentiel Pédologique introduces the notion of a basic *three-dimensional sampling unit*:

> **horizon**: homogeneous 3-dimensional volumes of soil material.

These are conceived as extending in three dimensions, generally parallel to the earth's surface. So a solum doesn't have horizons, it just allows us to see a cross-section of some horizons.

> (Note that this definition of 'horizon' is similar to the American definition [47]: **soil horizon**: A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, texture, consistency, kinds and number of organisms present, degree of acidity or alkalinity, etc.)

Finally, certain groupings of horizons are considered to occur systematically; these are defined as:

pedologic system: several horizons, associated in a specific 3-dimensional spatial pattern.

The pedologic systems typically occupy 1 000m^2 to 10 000m^2, similar to a polypedon.

3 Map scale, detail, and survey order

In this section I discuss the closely linked concepts of map scale, cartographic detail, categorical detail, and survey 'order' (type & density of observations, and map unit definition). The basic idea is that these should be in harmony, according to the survey user's needs, the surveyor's budget, and the natural landscape variation in the survey area.

3.1 Map scale

The publication scale of the soil survey map is a fundamental parameter that limits, to a large degree, other decisions about the survey. It is especially important to view the map scale from the point of view of the soil survey consumer: what can the map show?

Note that, even though vector GIS can mechanically enlarge or reduce maps, the original publication scale is still a critical feature of the GIS coverage.

3.1.1 Preliminary definitions

Conversion factors

Units: meters (m), centimeters (cm), millimeters (mm), kilometers (km), hectares (ha); squares of all excepts ha (which is already square)

Linear measure: 1m = 100cm = 1000mm; 1km = 1 000m

Or, using exponents: 1km = 10^3m; 1cm = 10^{-2}m; 1mm = 10^{-3}m

Area measure: 1ha = 10 000m² = (100m)²; 1km² = 100ha = 1'000 000m²

Or, using exponents: 1ha = 10^4m²; 1km² = 10^6m² (aren't you glad we use the metric system?)

When discussing scale and delineation size, we must always be clear whether we are referring to **ground** and **map** distances and areas. For example: 'ground meters' vs. 'map meters'. We can abbreviate these **_g** and **_m**, respectively. For example, ground meters can be abbreviated 'm_g' (i.e., **m**eters on the **g**round), etc.

Some measures can be assumed to refer to the ground, unless otherwise specified: hectares (ha), kilometers (km) and square kilometers (km²), so it is not necessary to write 'ha_g', just 'ha', and the same for km and km² (although it would be possible to measure something on the map in hectares!).

Similarly, **some measures can be assumed to refer to the map**, unless otherwise specified: millimeters (mm) and square millimeters (mm²), also cm and cm². So we can write 'mm', not 'mm_m' (although of course we can measure ground distances also in mm).

Basic idea: match delineation (polygon) size on map with the management area (polygon) on the ground. The concepts of scale are covered by a/o. Forbes *et al.* [31] Ch. 1, Dent & Young [24] Table 6.1 and in standard cartography texts [45].

3.1.2 Linear map scale

The **map scale** is the *ratio of map distance to ground distance*, both **linear** measures, and measured in the same units; it is **dimensionless** and always written as a *scale ratio* with unit numerator.

Scale ratio: map distance : ground distance; in the same units, so **dimensionless** (e.g. $m\_m\ m\_g^{-1}$, $cm\_m\ cm\_g^{-1}$). This is how the scale is usually shown on a map.

E.g. 1:25 000 ⇒ 1 cm on the map = 25 000 cm = 250 m on the ground

The map scale can be also be expressed as a *scale number* or as a *representative fraction*; they are inverses. Both may be used to convert between map and ground distances.

Representative fraction: (abbreviation **RF**) .The scale ratio as fraction, usually written in scientific notation, e.g. for a 1:25 000 map this is 0.00004 = 0.4×10^{-4} (i.e., 1 divided by 25 000). Mathematically it is dimensionless, but it is convenient to use some dimension, e.g. $0.4 \times 10^{-4}\ m\_m\ m\_g^{-1}$. Note that here the **map dimension is the numerator**; this is why the RF has a negative exponent of 10.

Scale number (abbreviation **SN**): Denominator of the scale ratio, and because the numerator of the scale ratio is always 1, also its mathematical *inverse*. E.g. for a 1:25 000 map SN = 25 000 = 2.5×10^4. The SN is convenient for working with numbers > 1 instead of small RFs. Mathematically it is dimensionless, but it is convenient to use some dimension, e.g. for a 1:25 000 map SN = $2.5 \times 10^4\ m\_g\ m\_m^{-1}$. Note that here the **ground dimension is the numerator**; this is why there is a positive exponent of 10.

Note: This definition of RF follows [1] instead of [31], who call what we are calling the SN the RF.

‘Large’ vs. ‘Small’ scale

Large-scale: a given ground area is represented by a **large** map (think about the wall covered with a large map sheet).

Small scale: a given ground area is represented by a **small** map (think about a pocket map).

These terms are completely **relative** to the area being shown. A ‘small scale’ map could be defined as map that shows the area of interest on one handheld sheet that can be comprehended at one or a few glances, in practice a sheet of paper no larger than ≈ 60x60cm; by contrast, a ‘large scale’ map anything larger, in particular a map that either in one sheet or in parts (atlas format) shows the area of interest on a sheet that can not be viewed in one or a few glances.

So a ‘small scale’ map of NL (≈ 45 000km² ≈ 150km x 300km); to fit in 60x60cm (in this case 30x60cm, the longer dimension on the ground, 300km, must fit in 60cm) the scale must be 1:(300km x 1000m km^{-1} x 100cm m^{-1} / 60cm) = 1:500 000 or smaller. By contrast, a ‘small scale’ map of the Enschede / Hengelo area (≈ 15x15km) would be 1:25 000 or smaller.

However some authors use an **absolute** scale definition of ‘large’ and ‘small’, depending on the map theme and intended use. For example Avery [1, Table 1] classifies soil maps as follows:

large scale:	1:2 500 - 1:25 000

medium scale:	1:50 000 – 1:150 000
small scale:	1:250 000 – 1:1’000 000.

Another way these terms are used is **relative to the intended use** of the map:

large scale:	Shows all features of interest, in detail, legibly
medium scale:	Shows many features of interest in detail, there is some generalization, the map is directly useful but it is understood that some finer features are not shown
small scale:	Almost all features of interest are generalized, the map gives an overview only and is not directly useful

Rather than argue about what is ‘large’ and ‘small’ scale, I prefer to leave the terms undefined, except to say that for any land area, a larger-scale map requires more paper than a smaller-scale map, and anything called a ‘large-scale’ map will show all features of interest.

3.1.3 Maximum location accuracy of mapped points

Before talking about delineations, we must talk about points.

Manual plotting of a **well-defined point** on a map: 0.25mm (¼ mm) maximum accuracy on the paper map [20]; this is an accepted **map accuracy standard**. Over the whole map, 90% of the well-defined points should be correctly located to this precision. This specification means that points must be *located* and then *plotted*; either procedure can lead to errors.

With **automated cartography** (GIS) the point can be *plotted* more accurately, but still there is paper shrinkage & expansion, uncertainty in the mechanical positioning of the plotting pen, and the location of the point in the field, so that the MLA is not much better, perhaps 0.1mm.

The less transferring from a geo-referenced source measurement, the more accuracy is possible. Ideal: precision GPS (≈1 cm precision in the field, therefore perfect precision at map scale), stored in a GIS with the same precision. But on a piece of paper there would still be plotting error; I estimate this is still 0.1mm

(Note that MLA is only a cartographic concept; if we have to find the mapped point ourselves in the field using the map as a source, that is a different problem.)

Computing maximum location accuracy [31, Table 1.2]

Multiply the SN by 0.25mm (0.1mm for GIS products) and then convert to ground meters.

> Example: 1:20 000: 20 000 mm_g mm_m^{-1} × 0.25 mm_m = 5 000 mm_g = 5 m_g (2 m_g for a GIS-produced map on stable paper with a high-precision plotter).

Interpretation: it is inherently impossible to plot a point closer than 5m on a 1:20 000 map. Also, any line can not possibly have a width <5m, since any point on the line could not be located more precisely.

3.1.4 Supply side: the delineation

Basic question: **what is the size of the areas shown on the map?** These are measured in **map area**, e.g. cm^2_m

<u>Minimum Legible Delineation (MLD)</u>

This is the smallest area (cm^2_m) **on the map** that be legibly delineated. It is a somewhat arbitrary **cartographic** concept.

According to the Cornell University group on Adequacy of Soil Resource Inventories [31], the MLD is defined as = **0.4 cm^2**_m = 40mm^2_m. This definition is based on the observation that in most published soil surveys there are rarely any delineations smaller than 0.4cm^2. Actually, somewhat smaller delineations *are* marginally legible, and therefore some authors, such as Vink [60], use a smaller area, MLD = **0.25 cm^2**_m = 25mm^2_m; this is also followed in some countries' soil survey programs, e.g. Netherlands [37, §29.2.2].

These MLD's can be expressed as **circles** of **radius** ≈ 3.6 mm (Vink: ≈ 2.8 mm); or, **squares** with **side** = 6.325 mm (Vink: = 5 mm).

Vink adds **a restriction on delineation width**: that **the smaller dimension ('width') of an elongated delineation** (e.g., a map unit following a river, or a seep at the base of a hill) **should be at least 2mm**; other authors, e.g. [37, §29.2.2], give 2mm as the absolute minimum width but recommend a 3mm minimum width. So, according to Vink, the smallest narrow delineation must have dimensions of at least 2mm x 12.5mm, to attain his MLD of 25mm; using the more conservative 0.4 cm^2 MLD and 3mm width, the smallest narrow delineation must have dimensions of at least 3mm x 13.$\underline{3}$mm. Note that a #00 pen draws a line of 0.3mm; so, such a line covers 10% of a minimum-width delineation.

In smaller delineations, the **actual line width on the printed map occupies a significant part of the delineation**; e.g. #00 pen (line width 0.30mm) to delineate a 0.4 cm^2 circle occupies 8.2% of the circle's area (assuming that half of the boundary line, i.e. 0.15mm, falls inside the circle); to delineate a 0.25cm^2 circle it occupies 10.3% of the area. The area actually covered by the line represent an 'arbitrarily classified' area, so should be minimized.

Also, in smaller delineations there is **no room for a symbol**.

The **boundary location accuracy of smaller delineations is a significant fraction of the delineation width**. E.g. 0.4 cm^2 square, each side $\sqrt{(0.4 \text{ cm}^2)} \approx 0.63$ cm = 6.3 mm; the MLA of a point on the boundary is 0.25 mm, i.e. 4%, and this is the best case. This implies that accurately drawing a boundary of small delineations is *inherently* inaccurate, no matter how well the boundary was located in the field.

<u>Minimum Legible Area (MLA)</u>

The MLA is defined as **the minimum ground area that is legible on the map**, defined as the MLD converted to ground scale; note that the **square** of the SN must be used, to convert the SN to an area

> E.g. for a 1:20 000 map, 0.4 cm^2_m $\times$ (20 000 cm_g cm_m^{-1})^2 = 0.4 $\times$ (4x10^8) cm^2_g
> = 1.6 $\times$ 10^8 cm^2_g ground area; convert this to m^2_g by multiplying by $(10^{-2})^2 = 10^{-4}$ m^2 cm^{-2},
> = 1.6 $\times$ 10^4 m^2_g; x 10^{-4} m^2_g ha^{-1}, = 1.6 ha.

Formula for the Cornell definition: MLA, ha = $(SN)^2 \times (4\times10^{-9})$. It is simpler to calculate in your head if you leave off the 1 000's from the SN, e.g. instead of 20 000 use 20; call this SNT, then the formula is just $(SNT)^2 \times (4\times10^{-3}) = (SNT)^2 / 250$

Simple formula (Cornell): MLA, ha = (Scale Number / 1 000)² / 250.

Example: $(20\ 000)^2 \times (4\times10^{-9}) = (2\times10^4)^2 \times (4\times10^{-9}) = 4 \times 10^8 \times 4 \times 10^{-9} = 16 \times 10^{-1} = 1.6$ha

Or, dropping the thousands, (20)² / 250 = 400 / 250 = 40 / 25 = 8 / 5 =1.6ha

Some other MLAs: 1:50 000 ⇒ 10ha; 1:24 000 ⇒ 2.304 ha ≈ 2¼ ha.

For the Vink definition, all areas are reduced by the ratio 25/40 = 5/8 = 1/1.6 = 0.625. So for example on a 1:20 000 map, the MLA of 1.6ha becomes 1.6 / 1.6 = 1ha. This can also be computed directly:

Simple formula (Vink): MLA, ha = (Scale Number / 1 000)² / 400.

Example: (20)² / 400 = 400 / 400 =1ha

There are two very useful relations for up- or down-scaling, both derived easily from the fact that the **area varies as the square of the linear scale**.

(1) **Halving** the **scale** quadruples the MLA; this is **doubling** the **SN**;
Doubling the **scale** divides the MLA by 4; this is **halving** the **SN**.

Examples:

1:100 000 = ½ x1:50 000 ⇒ 4 x 10ha = 40ha;
1:25 000 = 2 x 1:50 000 ⇒ ¼ x 10ha = 2.5ha

(2) **Dividing the scale by 10** multiples the MLA by 100; this is **multiplying** the **SN by 10**;
Multiplying the scale by 10 divides the MLA by 100; this is **dividing** the **SN by 10**

Examples:

1:500 000 = 1/10 x1:50 000 ⇒ 100 x 10ha = 1 000ha
1:5 000 = 10 x 1:50 000 ⇒ 1/100 x 10ha = 0.1ha = 1 000m².

1:200 000 = 1/10 x1:20 000 ⇒ 100 x 1.6ha = 160ha
1:2 000 = 10 x 1:20 000 ⇒ 1/100 x 1.6ha = 0.016ha = 160m².

Determining scale for a given MLA

We often want to turn the problem around and determine **what is the minimum scale for a given MLA**?

Formula with the Cornell definition of MLA: SN = [√(MLA, ha x 250)] x 1000. This works because $4 \times 10^{-3} = 250$.

Example: MLA 160ha: √(160 x 250) = √(40 000) = 200; 200 x 1 000 = 200 000; answer 1:200 000.

For the Vink definition, all scales calculated this way are reduced by the ratio $\sqrt{(40/25)} = \sqrt{1.6} = 1.2649$. Thus, a smaller-scale map will show the same MLA by the Vink definition. The easiest way to compute is by multiplying the SN calculated using the Cornell definition of MLD by $\sqrt{1.6}$. So for example a MLA of 160ha, the minimum scale becomes 1:(200 000 x $\sqrt{1.6}$) = 1:252 982. Notice that this is very close to 1:250 000.

Or, the direct <u>formula</u> for the Vink definition is: SN = [$\sqrt{(\text{MLA, ha} \times 400)}$] x 1000

<u>Optimum Legible Delineation (OLD)</u>

This is the optimum delineation size on a *readable* map. It is arbitrarily defined as 4 × MLD = 1.6 cm² (Cornell) or 1.0 cm² (Vink). This is based on observations of the ease of map use. **This is an arbitrary definition** (except that it must be ≥ MLD) based on **cartographic considerations**.

Sometimes the OLD is considered to be 2.5 x MLD = 1cm² (Cornell) or 0.625 cm² (Vink), so that the 1cm² OLD is a compromise which can fit into either definition of MLD. It is also easy to remember.

<u>Optimum Legible Area (OLA)</u>

OLD converted to ground scale, exactly as MLD is converted to MLA. So, 4 × MLA, by either definition of MLA.

<u>Average-size delineation (ASD)</u>

…and other statistics of the set of delineations. The ASD is the **arithmetic mean of the delineation sizes**, in map area (e.g. mm² or cm²_m), on the actual map. This characterizes how detailed is the map. Forbes *et al.* [31] give a method to estimate ASD using sampling circles. A GIS can easily give a histogram of the delineation sizes and calculate the average or any other statistic.

If the map has different textures (i.e., areas with different frequency distributions of delineation size and shape), calculate the ASD for differently-detailed areas separately; each of these *strata* of the map is evaluated separately.

Any meaningful statistic of the set of delineation sizes can be used instead of ASD, e.g. the median or the lowest quartile. The coefficient of variance or ratio of inter-quartile range to total range can be used as a measure of dispersion.

<u>Average size area (ASA)</u>

The ASD converted to ground area.

<u>Index of Maximum Reduction (IMR)</u>

The IMR is the factor by which **the scale of the map could be reduced before the ASD would become equal to the MLD**; i.e. the ASA = MLA. The IMR estimates whether the map is 'too fine', 'too coarse', or 'just right', cartographically.

The IMR can be directly calculated as the square root of the ratio of ASA to MLA (square root, because the area ratio must be converted to a linear ratio of map scales), or the square root of the ratio of the ASD to MLD. Either the Cornell or Vink MLD can be used.

Formula: IMR = √ (ASD / MLD) = √ (ASA / MLA)

In the case that we know the ASD, we can use a formula which already takes into account the MLD:

Formula (assuming the Cornell MLD, 0.4cm²): √ (2.5 × ASD), where the ASD is measured in cm².

Derivation: The √ is to convert from area measure to linear measure. The factor of 2.5 is the inverse of 0.4, so that if the ASD is 0.4cm², the IMR = 1.

Example: Suppose we measure an ASA of 160ha on a 1:50 000 map (MLA = 10ha). What is the IMR (using the Cornell MLD)?

Method 1: Direct calculation with linear measure: 160ha is the MLA of a 1:200 000 map (see above). So the 1:50 000 map could be reduced by a factor of 4 (in each linear dimension, 200 000 / 50 000 = 4) and still be legible, because in that case ASA = MLA = 160ha.

Method 2: Direct calculation from areas: The area ratio (ASA / MLA) is 160ha / 10ha = 16, so the linear ratio is the square root of this, i.e. √16 = 4.

Method 3: Using the formula: First we need to know the ASD; this is the ASA in cm² divided by the square of the map scale. In this case 160ha = 1'600 000m² / (50 000)² = 0.00064m² = 6.4cm². Then we apply the formula: √ (2.5 × ASD) = √ (2.5 × 6.4) = √16 = 4

An **arbitrary definition of the optimal IMR is 2.0**. In this case the **ASD = OLD**, because we arbitrarily set the OLA = MLA x 4, and √4 = 2. So in the example, IMR 4 > 2, in fact the scale could be reduced by a factor of 4 / 2 = 2.

An **IMR > 2** means that **the scale of the map could be reduced** (smaller sheet of paper) without losing legibility or accuracy; the published map's scale is too large.

An **IMR < 2** means that the map has too many delineations for its scale; **the scale should be increased** until IMR = 2, so that the map can be more easily read.

An **IMR < 1** means that the map scale is so small that the ASD < MLD, not just that that ASD < OLD (as is the case if 1< IMR< 2). **The average polygon is illegible**.

For the Vink MLD of 0.25cm², the IMR computed above is multiplied by √(8/5), i.e. more reduction is necessary to attain the 'optimum' scale. The direct calculation works the same but using the Vink MLA (0.25cm² converted to map scale, instead of 0.4cm²). The 2.5 (= 1/0.4) in the formula becomes (1/0.25) = 4.

Formula (assuming 0.25cm² MLD): IMR = √ (4 × ASD), where the ASD is measured in cm².

Derivation: The √ is to convert from area measure to linear measure. The factor of 4 is the inverse of 0.25, so that if the ASD is 0.25cm², the IMR = 1.

Example (same as with the Cornell definition): ASD = 6.4cm², applying the formula gives IMR = 5.0596 ≈ 5. Note the ratio of the IMR's computed according to the two definitions is 1.2649 = √(8/5). This agrees with the direct calculation. Using the Vink definition of MLD will always result in a greater IMR, i.e. the map can be reduced more (or needs to be expanded less) than using the Cornell definition.

See figure from [31] p. 3. This is of course a subjective measure of the legibility of a map.

3.1.5 Demand side: the decision area

Basic question: **what is the size of the areas to be managed**? These are measured in **ground area** (e.g., ha).

Minimum Decision Area (MDA)

The smallest area (km^2, ha, m^2) **on the ground** that the land user can treat differently; limited by 'size' of land use is defined as the MLD.

> Example: in a kitchen garden, individual plants can be placed by hand where the land-user wishes.
>
> Example: with large mechanized equipment, it is impossible to exploit fields below a certain size, often (in the midwestern USA) 40 acres (approx. 16 ha).

But, the land user typically wants to treat larger areas as a unit, hence the concept of the …

Optimum Decision Area (ODA)

Area that the land user *prefers* to treat differently; e.g. typical field size, typical residential development size… This corresponds to Vink's [59] **basic minimum area for planning**.

Example: midwestern USA: 160 acres (approx. 64 ha). It is usually uneconomic to treat smaller areas separately, because of the large equipment size and per-field setup time.

Often the ODA turns out to be about 4 times the MDA! Although this depends on the decision maker, this seems to be a psychological 'rule-of-thumb'. Note that this corresponds to the **supply-side** 'rule-of-thumb' that the OLD is 4x the MLD.

3.1.6 The ideal polygon map

With the above definitions, we can define the **cartographically-optimum polygon map**:

Criterion 1: **The scale of the map matches scale of use**: MDA = MLD; ODA = OLD

Criterion 2: The map has as large a scale as necessary to be legible, but no larger: IMR = 2

Criterion 1 implies that bigger isn't always better! If the map scale is too large, compared to the user's ODA (i.e., the IMR > 2), the user will not be able to see management areas; the detail of the map will confuse rather than help decision making.

3.1.7 Nature's Scale

The purely *cartographic* concepts treated above must be reconciled with the actual *soil pattern*:

"It is nature which controls the areal variability of soils, not soil scientists" [16]

"The complexity of the soil pattern determines the amount of detail that can be shown at a particular scale" [26, p. 91].

So, we can set a mapping scale, but the soil pattern may not respect it! (it may be too coarse or too fine). In this case we must adjust the **map unit definitions** or the **mapping scale** accordingly. I.e. the MLD is set by the map scale, and the level of categorical generalization is determined by the soil pattern within the MLD.

We will discuss this more under the topic 'Soil Survey Specification'.

3.1.8 Scale, order & delineation size

Soil and other natural resource surveys vary in publication map scale, intensity of observations, and techniques. These tend to co-vary.

See Table 6.1 in [24] and Table 2 in [1] The basic questions are

(1) What is a typical *map scale* (implies the *optimum legible delineation* corresponding to 1cm² or 1.6cm² on the map)?

(2) What is the *intensity* of the survey (density of observations) and what is the *method* by which observations are made?

Note that, regardless of map scale, **a common requirement for soil survey** [62, Table 3.3] is that there be, **on average, from ¼ to 1 field observation per cm² of *map***, i.e. each observation represents from 1cm² to 4cm².

However, in some organizations, e.g. Netherlands, a higher density is specified, e.g. 4 observations per cm², i.e. each observation represents ¼ cm² [37, §29.2.4]. This suggests that these organizations are publishing their maps at too small a scale. Comparing to Western's maximum number of observations per cm², i.e. one, we see that the Dutch maps have 4x the number of observations per cm², hence the scale is 2x too small. We reach the same conclusion by considering the IMR of most Dutch soil maps.

If the OLD is taken as 1cm² (Vink), this is one observation per one to four OLDs; taking the OLD as 1.6cm² (Cornell), this is **one observation per 0.625 to 2.5 OLDs**. Taking the OLD = 4xMLD, this is one observation per 4 to 16 MLDs (Vink) or **one observation per 2.5 to 10 MLDs** (Cornell).

(3) What is the *range of properties* (or, the degree of homogeneity) of the mapping units?

(4) What are the *names* of the mapping units?

(5) What is the *purpose* of the survey? I.e., what *interpretations* will be made from it?

We can relate this to the concept of *survey order* or *intensity level*, which we now discuss.

3.1.9 Survey order or intensity level

The USDA Soil Survey Manual [48] speaks of five *orders* of soil survey (very confusing term! because of the use of Order for the highest level of Soil Taxonomy); these are perhaps better called (as in Canada) *intensity levels*. The following is taken largely from Avery [1], Table 2, but using the Cornell MLD of 0.4cm² instead of the Vink MLD of 0.25cm² as originally used by Avery. It is clear that there is an intimate relation between intensity level and the concepts just discussed of scale and, from that, MLD and corresponding MLA. In fact, the inspection density is always congruent with the MLA.

Intensity level	*NRCS 'Order'*	*Inspection density*	*Publication scale*	*Minimum delineation size = MLA (0.4cm²)*	*Kind of map unit*	*Objectives*
Very high (1) 'Intensive'	1st	>4 per ha, i.e. > 1 per 2 500m²	1:2 500	0.025ha = 2 500m²	simple, detailed	LE for site planning; detailed engineering works
High (2) 'Intensive'	1st	1 per 0.8ha to 4ha, i.e. 25 to 125 per km²	1:10 000	0.4ha = 4 000m²	simple, less detailed	LE for intensive uses e.g. small fields, urban land; detailed surveys of sample areas; engineering works
Moderately high (3) 'Detailed'	2nd	1 per 5ha to 25ha, i.e. 4 to 20 per km²	1:25 000	2.5 ha = 25 000m²	mainly simple, some compound, moderately detailed	LE for moderately intensive uses at 'field' level; detailed project planning
Medium (4) 'Semi-detailed'	3rd	1 to 5 per km² i.e. 1 per 20ha to 100ha	1:50 000	10 ha	mainly compound, some simple, moderately detailed	LE for moderately intensive uses at 'farm' level; semi-detailed project planning; district-level LUP
Low (5) 'Semi-detailed'	4th	¼ to 1 per km² i.e. 1 per 100ha to 400ha	1:100 000	40 ha	almost always compound or general simple	LE for extensive land uses ; project feasibility; regional land inventory; district-level LUP
Very low (6) 'Reconnaissance;'	5th	<1 per km² i.e. <1 per 100ha	1:250 000	250 ha = 2.5km²	compound or dominant simple	national land inventory; regional LUP; LE for very extensive uses
Exploratory		none or opportunistic	1:1'000000 1:5'000000	40km² 1 000km²	categorical-ly general	get some idea of what soils exist in an unknown area

Note that 'higher' intensity isn't always better! It depends on the land use. E.g., for a national planner to get an overview of the production capacity of the country of staple crops, a detailed survey would be useless.

3.1.9.1 Intensity of observations: An example comparing Dutch and German surveys

There is some variation at any intensity. The following example is from a very interesting comparison of Dutch & German soil survey methods from [55].

Both the Dutch and Germans publish their soil maps mainly at 1:50 000 (which would classify as Intensity Level 4 in the table); however the Dutch make 12 to 20 observations per 100 ha = 1 km² (on the upper end of Level 4 and even to the lower end of Level 3), whereas the Germans make only 7 to 10 (on the lower end of Level 4).

In a 4 000ha area where two independent maps were compiled:

- the Dutch identified 197 delineations (ASA = 20.3ha ≈ **20ha**), whereas
- the Germans identified only 134 (ASA = 29.8 ha ≈ **30ha**)

i.e. the German map is 50% less detailed.

At 1:50 000 the OLD of 1.6cm² of map sheet = OLA of 40ha (4 x MLA of 10ha at 1:50 000).

We can compute the IMR as the **square root of the ratio of the ASA to the MLA**, i.e. the ***linear* reduction factor in scale** that would be necessary before the **ASA=MLA**. Therefore, the Dutch IMR = √(20/10) = 1.414 ≈ 1.5, whereas the German IMR = √(30/10) = 1.732 ≈ 1.75; **both maps are published at too fine a scale** (recall that an IMR of 2.0 is considered ideal, so that these IMR < 2 indicate that the map is too detailed, so that instead of being reduced until IMR = 2, it should be expanded).

The correct publication scale, for the actual mapped detail to be legible, should be

(2 / 1.5) = 1.3… x the actual publication scale (i.e., 1:37 500) for the Dutch map, and

(2 / 1.75) = 1.14 x the actual scale (i.e., 1:43 750) for the German map.

Another way to compute the IMR is to use the **formula: $\sqrt{(2.5 \times \text{ASD})}$**, where the ASD is in cm^2.

The 4 000ha test area corresponds to $40km^2 = 40 \times (10^5)^2\ cm^2 = 40 \times 10^{10}\ cm^2$ ground area.

Converting this to map cm^2, using the scale ratio 1:50 000, so dividing by $(5 \times 10^4)^2 = 25 \times 10^8$, we have a total map area of $(40 \times 10^{10}) / (25 \times 10^8) = (40/25) \times 10^2 = 1.6 \times 10^2 = 160cm^2$.

So, the Dutch map ASD = $160/197 = 0.81cm^2 \approx 0.8cm^2$; then applying the formula, IMR = $\sqrt{(2.5 \times 0.8)} = 1.414 \approx 1.5$. Similarly, for the German map, ASD = $160/134 = 1.19cm^2 \approx 1.2cm^2$; IMR = $\sqrt{(2.5 \times 1.2)} = 1.732 \approx 1.75$.

3.2 Cartographic vs. categorical detail

When we speak of the degree of ‘detail’ on a polygon soil map, there are two meanings: **cartographic**, referring to the **map**, and **categorical**, referring to the **legend**. (See example in [12], pp. 347-350)

These are very different concepts which lead to very different maps (abstract representations) of the same reality.

Cartographic (map) detail: How many delineations are shown on the map for a given land area, i.e. the pattern of polygons. A more **general** map has fewer and larger polygons than a more **specific** map, *at the same scale*. We can measure this by a map's ASD and IMR.

Categorical (legend) detail: What level of conceptual detail is implied by the entities shown on the map, i.e. by the legend. A more **general** legend makes fewer separations, based on fewer categories and more general classes, than a **specific** legend.

In a legend based on a hierarchical soil classification such as Soil Taxonomy, a more 'general' legend corresponds to using the higher taxonomic levels as legend entities. This almost always corresponds to more legend categories at lower taxonomic levels.

In an *ad-hoc* or local legend, the more 'general' legend categories have wider ranges of soil properties.

Example using *levels of Soil Taxonomy* to indicate level of categorical generalization: In the Edgecombe County, NC soil survey, going from most to least categorically general:

(1) A map of **Orders** has only 4 categories: { Ultisols, Entisols, Inceptisols, Alfisols } (≈ 90% Ultisols, <1% Alfisols)

(2) A map of **Suborders** has 8 categories: { Udults, Aqults, Fluvents, Aquents, Psamments, Ochrepts, Aquepts, Aqualfs }

(3) A map of **Great Groups** has 12 categories, { Albaqualfs, Dystrochrepts, Endoaquults, Fluvaquents, Hapludults, Humaquepts, Kandiudults, Paleaqults, Quartzipsamments, Udifluvents, Udipsamments, Umbraqults };

(4) A map of **Subgroups** has 21 categories: { Typic Albaqualfs, Fluvaquentic Dystrochrepts, …, Typic Umbraquepts }. Some of the important Great Groups have several subgroups, e.g. the Aquic, Arenic, and Typic Hapludults.

(5) A map of **families** has 35 categories (families): { Fine, mixed, active, thermic Typic Albaqualfs, …, Fine-loamy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquults }. At this level, several important subgroups have several families. E.g. the Typic Paleaquults have three families: (1) Fine, kaolinitic; (2) Fine-silty, siliceous; and (3) Fine-loamy, siliceous (all thermic). These are essentially divisions by family particle size class, which is very important for water-holding capacity.

(6) A map of **Soil Series** has 38 categories (series) { Altavista, Autryville, … Wehadkee, Wickham } In this case, only a few families have more than one series. Example of a finer distinction: State & Wickham series are both Fine-loamy, mixed, semiactive, thermic Typic Hapludults, differing only in the color of their argillic horizons (Wickham is redder than State).

(7) The actual legend has 52 map units, which are **phases of soil series etc**. { AaA, AuB, AyA, …, Wh, WkB }. The phases are mostly based on slope class.

In this example, the greatest increase in categorical detail, in terms of number of categories, comes when mapping (1) families vs. subgroups (from 21 to 35, a 67% increase) and (2) phases vs. series (from 38 to 52, a 37% increase). There is significant increase in *interpretive precision* at each level.

<u>Cartographic generalization can be considered *independently* of categorical generalization:</u>

(1) **Cartographically detailed, categorically detailed**: A detailed pattern of narrowly-defined classes, e.g. phases of soil series. The scale must be large enough to show the pattern of polygons (IMR > 1). **This is typical of a *detailed* soil survey.**

(2) **Cartographically detailed, categorically general**: A detailed pattern of broadly-defined classes. In most cases, this is a **mismatch of concepts**: many boundaries that would be shown on a categorically-detailed map will be eliminated (because adjacent polygons are in the same higher category); the IMR will be high, showing that the map scale is too large for the level of categorical detail.

(3) **Cartographically general, categorically detailed**: A few large map units of narrowly-defined classes. In most soil landscapes this is impossible: the purity of the large map units will be too low; therefore the map units will have to be described as **associations of detailed categories**; with a few lines showing the main landscape elements. This can be useful if the landscape pattern within the general cartographic unit can be recognized on the ground or on detailed airphotos. **This is a typical *semi-detailed* soil survey**, or for a cartographic generalization of a detailed soil survey at smaller scales.

(4) **Cartographically general, categorically general**: A few large map units of broadly-defined classes. **This is a typical *reconnaissance* soil survey**, and can be useful to give an overview of important soil properties. It usually ignores inclusions.

A figure may make these relations clearer.

		Level of **Cartographic** Detail	
		General	Detailed
Level of **Categorical** Details	General	(4) associations of WRB 2^{nd}-level groups; 1:250k; regional inventory with low locational value	(2) consociations of WRB 2^{nd}-level groups or families; 1:25k. *Mis-match*, high IMR.
	Detailed	(3) associations of phases of soil series ("2-stage"). Semi-detailed SRI at 1:50k to 1:250k	(1) consociations of phases of soil series; 1:25k. Detailed SRI

So, models (1) and (4) tend to be the most successful for useful soil maps; (3) is useful for small-scale maps of an area that has been surveyed at a larger scale and for 'two stage' maps.

3.3 Reducing a polygon map to a smaller scale

The cartographic result of a mechanical reduction in map size (i.e., a decrease in scale) is to each delineation smaller, in accordance to the square of the ratio of scales. The Minimum Legible Area is increased correspondingly, i.e. proportionally to the reduction in *area* scale. For convenience, we define the **reduction ratio** (RR) as the ratio of the two linear scale numbers:

Reduction ratio $\equiv SN_{new} / SN_{original}$

> For example, if a map is originally compiled on a 1:50 000 base and then reduced to 1:100 000, the linear scale is reduced by 2x, and RR = 100 000 / 50 000 = 2. Therefore, the **area** scale is reduced by 2^2 = 4x. The MLA increases from 10ha to 40ha.

The Index of Maximum Reduction (IMR) is necessarily reduced proportionally to the RR, because the IMR is also a ratio of linear (not area) measures.

> In this example, suppose that the IMR at 1:50 000 was 2.5; at 1:100 000 it is 2.5/RR = 2.5/2 = 1.25.

This presents two cartographic problems:

1. **Some delineations become illegible**, i.e. those where the MLA of the larger-scale map is illegible on the smaller-scale map. In the above example, any delineation between 10ha and 40ha (legible at 1:50 000) is now illegible at the reduced scale (1:100 000.)

2. **The IMR is smaller**, and may indicate **overall illegibility** of the map, even if individual delineations are large enough. Recall that an IMR =2 is considered optimal; thus unless the original IMR was $\geq 2\times$(RR), the IMR will be <2 after reduction.

In the case of soil maps, **there is no purely cartographic solution**. We must, of course, mechanically throw out illegible polygons and assign their area to a surrounding or adjacent polygon. In the case of 'islands', they must be absorbed by their surrounding polygons. But what about a small polygon that borders on several larger polygons? Or a group of small polygons that together would be >MLD at the new scale? The **landscape pattern** at the new, smaller, scale must be analyzed.

Even in the case of 'islands', the remaining large polygon has a different composition, i.e. different proportion of soils. The remaining map units must be re-examined, re-described and **possibly re-named** in light of their new composition. See the next § for rules on naming map units. A common situation would be several consociations now described as associations, with known landscape patterns of the components.

Note that the GIS *can* perform a mechanical generalization, e.g. by eliminating polygons that are too small and merging them with their largest neighbor. But that is purely cartographic, and we must consider the categorical implications.

> For example, think of a pitted glacial outwash plain, with two components: deep, well-drained gravelly loams on the higher positions, and poorly-drained, organic matter-rich, fine textured soils in the 'potholes' in the depressions. These can easily be delineated on an airphoto. Supposing that the potholes occupy approximately 1ha each, they can be legibly delineated at 1:16 000 or larger, e.g. 1:12 500 (MLA = 0.625ha). We have a map that looks like Swiss

cheese, where the potholes are clearly shown. Suppose that the potholes occupy 20% of the total area, and the gravelly loams the other 80%.

Now, suppose we reduce the 1:12 500 map to 1:25 000 (RR = 2). The MLA is 0.625×4 = 2.5ha, much larger than the potholes. They become illegible, and must be deleted. Their area is now included in the surrounding polygons.

If we omit them from the map, suddenly we don’t have Swiss cheese, we have one large map unit, consisting of 80% gravelly loams and 20% potholes. Thus we **must** change the legend! Since the potholes are strongly contrasting and limiting, even though there are only 20%, they must be included in the map unit name (see later §); since these two landscape components can obviously be mapped separately at a larger scale (i.e., the original scale), the new map unit is an association. The smaller-scale map is still categorically-detailed, but cartographically-general.

3.4 Enlarging a polygon map to a larger scale

Here we consider the case where a map is printed at a larger scale than the source documents. Since we can never add information, the larger-scale map is **misleading**, because the MLD at this larger scale were in fact not mapped. We can not assume that there are no areas larger than the MLA of contrasting soils. Also, boundary lines look smooth; they may in fact be more detailed at the larger scale, but they were not mapped. It is very rarely justified to print a map at a larger scale than its original source.

At a larger scale, line and point entities that represent soil bodies should be represented as polygons, assuming that the line width or point radius was controlled by the original map scale.

4 Map units of area-class maps

The **map legend** is the list of categories or 'map units' shown by an area-class or point-class map. In other words, it is the **information content** of the map: what are in those polygons or at those points? In this section we first discuss the concept of 'homogeneity' of map units, then the types of names that can be given to map units, and finally a field key.

Key concepts:

- Map unit, delineation
- Homogeneous vs. compound map units
- Inclusions & components: similar vs. dissimilar; limiting vs. non-limiting
- Consociation, association, complex, (undifferentiated group, unassociated soils)
- Map unit names: local, land characteristics, land qualities, from a classification system, series
- Soil Taxonomy as a mapping legend: pro and con
- The Soil Series; natural vs. taxonomic Series; (the taxadjunct to a Soil Series)
- Phases: properties of the surface layer; internal soil properties; site properties

4.1 Map units classified by their categorical purity & soil pattern

A **map unit** of an area-class map is a **set of delineations**, all supposed to have the 'same' properties except for their geographic position. We need to be able to name map units consistently, in a way that users will understand.

One map unit ⇔ many delineations

> Note: it would be possible, in theory, to make an area-class map with each delineation characterized separately. This ignores the theory of soil genesis, i.e. that similar soil-forming factors should produce similar soils. This is true both for individual soils and patterns of associated soils. Very rarely would only one delineation in a survey area have a unique soil or pattern of soils.
>
> Now, because of the **limited sampling** inherent in most soil mapping exercises, it is entirely possible and indeed probable that transects or grid samples in two delineations of the same landscape unit result in different proportions of constituents and inclusions. But if this is within **sampling error**, and in the absence of confirming information, it is better to keep the map unit together, and not split just on the basis of somewhat different sampling results.

One basic distinction is between **homogeneous** and **compound** map units. This refers to the **internal composition** of the map unit. These terms are **relative to a specific classification system** or **list of soil properties and their diagnostic limits**. In other words, a 'homogeneous' map unit of a categorically-general map may be the same as a 'compound' map unit of a categorically-detailed map.

Note: in some cases we do know that there are real differences **between delineations** of the same map unit, but either they are not consistently mappable or else the differences would complicate the legend unnecessarily. Sometimes the soil survey report will give supplementary information, e.g. 'in the northern part of the survey area, the soils in this map unit have a coarser-size sand fraction…'.

Scheme of map unit types (types written in **bold** are most important)

1. Homogeneous
- **1.1 Consociation**
- 1.2 Undifferentiated Group*

2. Compound
- **2.1 Association**
- **2.2 Complex**
- 2.3 Unassociated Soils*

* (Not all delineations have the same composition, see below)

These have the following sorts of **names** (here using examples of soil series); see [58] for details.

1. Homogeneous
- **1.1 Consociation**: 'Norfolk soils'
- 1.2 Undifferentiated Group: 'Norfolk, Goldsboro, and Wagram soils'

2. Compound
- **2.1 Association**: 'Norfolk-Lynchburg association'
- **2.2 Complex**: 'Norfolk-Lynchburg complex'
- 2.3 Unassociated Soils: 'Norfolk or Dothan soils'

We now discuss these map unit types in detail.

Homogeneous map units:

Definition: **'All' the locations within each delineation the map unit have the 'same' characteristics, and classify to the same named soil**(s), at the level of the classification used in the map unit name.

Exception: Undifferentiated groups don't have the same soil in each delineation, see below

For purposes of **interpretations** (e.g., land evaluation) we assume that a homogeneous map unit has the '**same' values of all Land Characteristics** over all its extent. Land characteristic values are typically measured in ranges, and in a homogeneous map units, these ranges cover 'all' the variability in the map unit. The LC values aren't identical, but they are in reasonably narrow (i.e. interpretable) ranges.

The more general the classification, the wider the range of LCs in a 'homogeneous' map unit. Still, for interpretive purposes, it is considered a single entity.

In reality, very few soil bodies defined by categorically-detailed classes or relatively narrow property ranges are truly homogeneous at mappable scales; see the next §, 'Inclusions'. In soil survey, we really mean **'homogeneous enough for most interpretations'** or **'as homogeneous as possible to map with reasonable effort'**, with a 'small enough' content of contrasting soils.

Compound map units:

Within each delineation there are **significant areas of more than one contrasting class of soil**, so that different locations in the map unit may classify as different soils, at the level of classification used in the map unit name. This kind of map unit is made up of two or more '*homogeneous' constituents*, where 'homogeneous' is defined as in the previous ¶.

Exception: Unassociated soils don't have the same composition in each delineation, see below

For purposes of **interpretations** (e.g., land evaluation) we assume that a compound map unit **does not have the 'same' values of all Land Characteristics** over all its extent; in general, significant areas of each delineation will have different properties and use potentials.

Compound map units are used in **three situation**s:

(1) when **the map scale is too small** to show constituents that otherwise could be mapped; and

(2) when the constituents **can't be separated at any realistic map scale**.

(3) when there has **not been enough sampling** to establish whether (1) or (2) applies, but it is known that more than one contrasting soil occurs in the map unit.

4.1.1 Inclusions

Many studies have shown that, in reality, there are almost no truly homogeneous map units at semi-detailed or detailed categorical levels, at mappable scales. However, we can still keep the distinction between 'predominantly' homogeneous units and true compound units, with the concept of **inclusions**.

Exception: some extremely homogeneous depositional environments, e.g. sand dunes; some very old weathering surfaces; these may be homogeneous at almost any level of categorical detail.

Definition: An **inclusion** in a map unit is a soil individual (pedon) contained within the boundaries of a map unit, that is **not classified in the soil class by which the map unit is named**, or is **outside the range of properties** given for the legend category.

Note that at higher categorical levels, or with more general definition of classes, the proportion of inclusions automatically decreases.

Why are there inclusions in an area-class map?

1. The area is **too small to delineate at the map scale** (even if the surveyor can clearly see it).

   Example: a small sand dune in an otherwise flat cover sand landscape.

2. The component covers a large enough area to delineate, but the **location can not be mapped consistently** in the field or on the airphoto.

   Example: in a map unit named for a soil that is moderately deep to bedrock, there may be significant areas ('pockets') of deeper soils. If we dig a deep trench (for example, for a pipeline) we can see these pockets and could map them. In a humid climate, there may be no obvious surface expression (since the moderately deep soil is deep enough to supply sufficient moisture), so they can't be mapped. Yet, they are different soils and have different interpretations, e.g. for engineering works that extend into the subsoil, such as pipelines.

Another example is if dense vegetation or cloud cover makes it impossible to see the landforms on the airphoto, e.g. in some areas the Brazilian Amazon.

3. The component is **deliberately** included in a map unit named for another soil, to avoid **excessive map or legend detail**, even though the component is mappable. This is only done if the two soils act similarly for all uses. Often these 'inclusions' are actually separate delineations, even on different landscape positions.

   Example: small, mappable delineations of alluvial soils where the layering has been obscured by pedogenesis (Fluventic Dystrochrepts) may be included in a map unit where the soils still show the layering (Typic Udifluvents), in order to avoid creating an extra legend category. If the textural profile is similar they will behave the same. Or will they? My rule is: if you can map it and describe it, do so; it may prove to be important for some uses; the computer can handle any number of legend categories. Also, use of this kind of inclusion obscures the true soilscape pattern for the knowledgeable soil map user. In the present example, the Inceptisols probably occupy slightly higher positions with less current and past flooding.

   This is a correlation decision, *not* dictated by the mapping scale or soilscape pattern.

Examples of inclusions

Edgecombe County, NC. (Atlantic Coastal Plain), map units named with Soil Taxonomy 1975. Very large delineations (≥1 000ha) of the suborder Udults could be defined with no inclusions; also large areas (≥40ha) even of the great group Paleudults. However, at the family level, there are four competing mixed, mesic Paleudults, all intergrades to the 'central' or 'key' series Norfolk:

1. **Norfolk series: fine-loamy** ('key' soil)
2. Marlboro series: fine
3. Aycock series: fine-silty
4. Wagram series: fine-loamy, arenic
5. Goldsboro: fine-loamy, aquic

They typically occur in large relatively homogeneous areas, presumably depending on the original particle-size distribution of the sediments, and in the case of Goldsboro, on the landscape position:

1. Norfolk series: fine-loamy sediments, near drainage ways and on gentle slopes
2. Marlboro series: fine sediments, near drainage ways and on gentle slopes
3. Aycock series: fine-silty sediments, near drainage ways and on gentle slopes
4. Wagram series: fine-loamy sediments with somewhat coarser sand fraction, nearer to drainage ways, near scarps
5. Goldsboro: fine-loamy sediments (Norfolk), far enough from drainage ways or on flatter and lower landscape positions, so that the water table comes into the profile during much of the year

However, it is possible to find individual pedons of any of these series within a delineation; e.g. a slightly siltier pedon (Aycock) or clayier pedon (Marlboro) or a pedon with weak groundwater influence (Goldsboro) or a slightly coarser pedon with a thicker sandy surface layer (Wagram) within a predominantly Norfolk area, because of differences in original sediment and landscape position.

Result: even a 'good' delineation of Norfolk has 10-20% of these inclusions, for different reasons, depending on the inclusion:

The Wagram areas can typically be identified in the field by their coarser, lighter surface layer; the Goldsboro by their slightly lower elevations and darker surface color. They are included because the areas are too small to delimit. Aycock and Marlboro differ primarily in subsoil texture, and are very difficult to distinguish from Norfolk from external characteristics; the surveyor must auger to the control section. They are included because they can't be mapped.

In fact, map units named for the Norfolk, Aycock and Marlboro series almost always have significant amounts of one or the other similar series, and are named for the dominant series (= subsoil particle-size class) which was determined by augering to the control section.

4.1.1.1 Similar & dissimilar inclusions

Clearly, not all inclusions affect the usability of the soil map to the same extent. At any categorical level we can separate 'similar' and 'dissimilar' inclusions, also called 'components'. The basic distinction is whether the components act more or less alike. According to the US National Soil Survey Handbook:, §672.05:

> "**Dissimilar** components are those that differ enough from the named components to **affect major interpretations**. Conversely, **similar** components are those that differ so little from the named components that their **soil interpretations for most uses are very similar**."

In this view, 'similarity' is primarily an **interpretive** concept (survey user's point of view). However, they can also be viewed from the survey producer's point of view. Avery [1, p. 64] defines similar components as follows:

> "**Similar** components are conceived as those that: **occur together** in landscapes, are **alike in most properties**, and **share the class limits** of the **diagnostic properties** in which they differ".

Note that the 'diagnostic properties' are defined according to the classification system. They should interpret almost the same for most land uses. Therefore, the two definitions usually identify the same soils as 'similar'.

> Example (Edgecombe County, NC): Areas of Goldsboro soils (ST 1975: Fine-loamy, kaolinitic, thermic Aquic Paleudults) within map units of Norfolk soils (ST 1975: Fine-loamy, kaolinitic, thermic Typic Paleudults). These formed on the same parent material, form a drainage sequence and occur together on the landscape, differ only in one diagnostic property, namely subsoil wetness, as well as accessory properties such as color, and in the diagnostic property they share the class limit: aquic/typic. The increased subsoil wetness only marginally affects most interpretations. Some crop yields may be higher in dry years and lower in wet years, but there will be no extreme differences. So Goldsboro is considered to be 'similar' to Norfolk, both in interpretation and in diagnostic properties.

Note that the **soils can classify differently at any level of Soil Taxonomy and still be similar**! It depends on how much the soil would have to change to be classified differently.

> Example 1: Typic Udifluvents (Entisols) differ from Fluventic Dystrochrepts (Inceptisols) only in that the Fluvent does not have a cambic horizon because of thickness. This is suggested by the use of the 'Fluventic' subgroup name to indicate the intergrade.

Example 2: Typic Hapludoll (Mollisol) vs. Typic Eutrudepts (Inceptisol); differ only in the thickness of the epipedon (mollic vs ochric); the ochric epipedon of the Eutrochrepts meets all requirements of the mollic epipedon except thickness. Neither have an argillic horizon, both have high base saturation.

Example 3: Ultic Hapludalf (Alfisol) vs Typic Hapludult (Ultisol), differ only in base saturation in the argillic horizon (35-60% vs. <35%).

<u>Dissimilar components</u>

Components that are not 'similar' are called 'dissimilar'. This can be for one or more of the following reasons:

1. **occur on different major landscape components**;
2. **differ in more than a few properties**, or
3. **do not share the class limits** of the **diagnostic properties** in which they differ.
4. although sharing class limits, the classes are too wide, and **major interpretations of the central concepts are significantly different**.

Examples of these kinds of dissimilar components:

(1) A completely different landscape component, e.g. small steep eroded gullies in an otherwise deep, flat plain;

(2) Differences in depth, texture, drainage class, plasticity…, i.e. **so many differences that the soils have markedly-different behavior**; in other words, really different soils for most purposes.

Note that some single differences, notably parent material, can imply many accessory differences, making the soils dissimilar.

(3) **Another class limit** comes between the dominant soil and the inclusion, i.e. the soils are separated in conceptual property space.

Example: (Edgecombe County, NC): Areas of Lynchburg soils (ST 1975: Fine-loamy, siliceous, thermic Aeric Paleaquults) within map units of Norfolk soils (ST 1975: Fine-loamy, kaolinitic, thermic Typic Paleudults). These differ by two drainage classes, so much so that Lynchburg soils are Aquults instead of Uddults. The Goldsboro soils come 'between' these two in the drainage sequence: Norfolk-Goldsboro-Lynchburg-Rains-Pantego. So an area of Lynchburg in a Norfolk map unit is considered a *dissimilar* inclusion. It will seriously affect many interpretations. For most upland crops, areas of Lynchburg soils severely limit rooting depth during the first half of the growing season, because of wetness. They are wetter during the winter, limiting field operations (or else they must be artificially drained).

(4) If the **categorical level is high**, e.g. families of Soil Taxonomy, **even adjacent classes** at that categorical level **may be dissimilar**.

Example, soils in the same subgroup, with fine vs. clayey-skeletal family particle-size classes. Although these share a class limit of 35% coarse fragments in the control section, the range of 'fine' is 0-35% and of 'clayey-skeletal' of 35-90% (limit of 'fragmental' class). The central concepts of these families are probably 15% and 50% coarse fragments, which have very different interpretations for available water capacity, rooting volume, tillage, macropores etc.

The 1993 Soil Survey Manual explains the reasoning behind similar and dissimilar components as follows:

"In the definition of map units, **judgement must be exercised about the effects of inclusions on management** and about how much effort is justified to keep the amount of inclusions small. In exercising these judgements, visualizing two kinds of differences between components is useful. If differences are small, the components are compared as similar. If differences are large, the components are contrasted as dissimilar.

Similar components are alike or much alike in most properties and share limits of those diagnostic properties in which they differ. **Differences are beyond the limits of the reference taxon or phase class, but they generally are within or slightly beyond normal errors of observation**. Because only a few limits are shared or the range is small, interpretations for most common uses are alike or reasonably similar and the interpretive value of a map unit is not affected.

Dissimilar components on the other hand, differ appreciably in one or more properties, and the differences generally are great enough to affect major interpretations."

4.1.1.2 Limiting & non-limiting dissimilar components

Dissimilar components can further be classified as **limiting** or **non-limiting** for specific land uses.

Limiting the dissimilar component is **less suited to the land use**. Its presence has a significant impact on predictions for the map unit as a whole.

Example (NC): an area of Lynchburg in a map unit of Norfolk for a deep-rooted crop that needs free drainage, e.g. tobacco. These will have considerably lower yields and will delay field operations.

Non-limiting: the dissimilar components is **equally or better suited to the land use**. According to the 1993 Soil Survey Manual:

"If an inclusion **does not restrict the use of entire areas or impose limitations on the feasibility of management practices**, its impact on predictions for the map unit is small. Inclusions of soil components that have less severe restrictions on use than the dominant soil of a map unit do not adversely affect predictions about the unit as a whole. They may even be beneficial. Such inclusions are **non-limiting** and the interpretive purity of a map unit for most interpretations is not altered."

Example (NC): an inclusion of Norfolk in an area mapped as Lynchburg, for most field crops.

Note that the terms 'limiting' and 'non-limiting' are ***relative to the land use***, and the situation could be reversed for a different land use. However, field mappers are aware of the dominant land uses, and usually attempt to reduce the limiting inclusions by various strategies, e.g. 'pushing' a transitional boundary line towards the 'better' soil.

Spot symbols

Dissimilar components will usually have **clearly different interpretations** for most land uses. The SSM says:

> "Soils that can not be used feasibly for the same purposes as the surrounding soil are especially crucial. They are separately delineated if the map scale permits… **areas too small to delineate [should] be identified and located on the map by special symbols**".

These are the **spot symbols** for strongly-contrasting areas: For example: wet, sandy, steep, rocky. By definition, the spot is placed in the center of the area and occupies an area up to the size of the MLD at that scale. A spot symbol automatically increases the purity of its enclosing map unit.

4.1.2 Homogeneous map units

Keep in mind that there are no truly 'homogeneous' map units, only 'homogeneous enough' for most purposes. The 1993 Soil Survey Manual (SSM) says:

> "In all soil surveys, virtually every delineation of a map unit includes areas of soil components or miscellaneous areas that are not identified in the name of the map unit".

This is especially true when narrowly-defined taxa (e.g. Soil Series within Soil Taxonomy) are used to classify the 'soil components' of the previous comment.

4.1.2.1 Consociations

These are as 'homogeneous as can be expected' in detailed mapping. The 1993 Soil Survey Manual says:

> "In a consociation, delineated areas are dominated by a **single soil taxon**… **and similar soils**"

where 'similar' is defined above.

The definition of consociation comes from experience in actual landscape variability in detailed soil mapping. There are various 'rules' which are not always feasible or measurable; the correlator can always use **judgement**, based on the effects on the interpretability of the legend.

All five of the following conditions must be met for the map unit to be called a 'consociation'.

1. **At least 50% of the area of the consociation is classified in the named taxon** (typically phase of series or family) or its taxadjunct (see below) **in *every* delineation** of the map unit.

   > So, if the map unit says 'Norfolk loamy sand, 0-2% slopes', at least 50% of the pedons must classify to the Norfolk series, they must have a loamy sand topsoil, and have slopes between 0% and 2%. Note that *all* delineations must meet this criterion, *not* the total area of the map unit taken as a whole.

   However, the National Soil Survey Handbook, §627.05, allows a little room for judgement here: "Note: Some soil consociations may be **less than one-half the named soil** if most of the remainder of the map unit consists of **two or more soils** that are **similar to the named soil**. The unit is named for the dominant soil." The idea here is that we don't name a complex just on the basis that no single soil is ≥50%.

2. **At least 75% of the area of the consociation is classified in the named taxon or in a *similar* taxon**, again in ***every* delineation** of the map unit. . Note that the concept of 'similar' taxon is established by the classification system and by the detail of the interpretations.

In the Norfolk example, 75% of the pedons must be Norfolk, Goldsboro, Aycock, Marlboro or Wagram (see previous example), with either a loamy sand, fine or very fine loamy sand, sandy loam, fine or very fine sandy loam topsoil, and 0 to 6% slopes The class limit of 2% slopes is with a 2% to 6% class, therefore slopes up to 6% are considered to be 'similar'. Different delineations can have different similar taxa.

Note that this total of 75% must in general have ≥ 50% of the named taxon, because of rule (1), and the rest is then made up by similar inclusions, for a total of ≥ 75%. If there are e.g. 60% of the named taxon, then the similar inclusions must be ≥ 15%.

If Rule (1) is relaxed, Rule (2) becomes just an extension of Rule (1), with a higher required proportion.

3. As a result of (2), **no more than 25% of the area can be *dissimilar* inclusions, even if *non-limiting***.

For the Norfolk example, there are no dissimilar, non-limiting inclusions. For a delineation of 'Lynchburg fine sandy loam, 0 to 2 percent slopes', Norfolk would be a dissimilar but non-limiting inclusion; so that there could be ≤25% Norfolk pedons (well-drained) within a mapped Lynchburg area (somewhat poorly drained).

4. **No more than 15% of the area can be can be *dissimilar limiting* inclusions**.

This is quite surprising, if you stop to think about it. Up to 15% of the area of a delineation could be an 'unusable' soil for a particular land use, and the delineation is still called 'homogeneous'! But, this comes from experience with actual landscapes at medium mapping scales.

For the Norfolk example, this implies that there must be ≤15% Lynchburg (somewhat poorly drained) or wetter, pure sand topsoils or thicker loamy sand (grossarenic subgroups), or slopes > 6%.

5. **No *single* dissimilar limiting inclusion can exceed 10% of the area**. This implies that the 'small' areas of strongly contrasting soils should be of different types. If one strongly contrasting soil occupies >10% of the area, it should be recognized in the map unit name, and the map unit must be compound. One way out of this is to indicate the dissimilar limiting inclusions by **spot symbols**; then those areas do not count for the purposes of these rules.

But, the SSM leaves the definition open for occasional exceptions that cover a small area of the total map unit:

"The amount of dissimilar inclusions in an individual delineation of a map unit can be greater than this if no useful purpose would be served by defining a new map unit."

In practice, this means that some delineations have different minor soils than the majority, so that new map units aren't created just for a few delineations.

<u>Naming consociations</u>

Consociations are named for the **dominant taxon**, at any **categorical level**, using the plural. In the case of ST families, the family criteria often go at the end. Examples:

Norfolk loamy sands, 0-3% slopes
Norfolk soils (this can be either series or family, the legend explains which)

Typic Kandiudults, fine-loamy, kaolinitic, thermic
Udipsamments

How do we determine whether we have obeyed these limits? In general we don't have enough resources for a statistically-valid sample that would guarantee the required degree of purity. We will see some sampling schemes later.

4.1.2.2 Undifferentiated groups

Criterion (1), above, ensures that we don't group similar soils that occur in different geographical areas into one map unit and call it a consociation. But we may have several soils that interpret the same for all anticipated land uses. The correlator might want to simplify the map legend by joining several fairly small legend categories that would, separately, be consociations into one legend category. This is allowed, by the SSM, by the use of an **undifferentiated group**. This is not 'homogeneous' in composition, because different delineations have different soils; however, it *is* 'homogeneous' with respect to interpretations.

> Example from NY State (USA): The Bath and Lackawanna series are in the same ST family (Coarse-loamy, mixed, mesic Typic Fragiochrepts) and differ only dominant hue (Bath: 10YR; Lackawanna: 5YR) because of differences in the color of the parent sedimentary rocks. In some survey areas (e.g. Broome County, NY) there are areas of both soils, but not together: the western section of the county has only Bath and the eastern section only Lackawanna, because of different facies of the same sedimentary series. Suppose that 80% of the delineations in the total survey area are Bath and 20% are Lackawanna, without inclusions.
>
> Since these two soils interpret the same for all land uses, and the total area of Lackawanna soils are relatively small in the survey area, the correlator might want to simplify the map legend by including the Lackawanna delineations with the Bath delineations in one legend category. If the correlator defines a map unit named 'Bath', it would be a consociation *except* that the Bath soil does not occur *at all* in 20% of the delineations (they are all 'red' soils); this violates rule (1) of the consociation.

The undifferentiated group, then, has as its main criteria:

1. The use potential and management methods for the named components are essentially the same;

2. The components do *not* occur together in a consistent pattern in each delineation.

If the map unit fails one of these criteria, it is a compound map unit (see next §)

Also, they must meet homogeneity criteria, similar to those for the consociation:

1. **At least 50% of the area of the undifferentiated group is classified in the named taxa** or their taxadjuncts, **in *each* delineation** of the map unit. *Different delineations* can use *different taxa* to meet this criterion.

2. **At least 75% of the area of the undifferentiated group is classified in the named taxa or in *similar* taxa**. This is like the consociation, except there is more than one taxon, and they don't have to occur together in most delineations.

3. As a result of (2), **no more than 25% of the area can be *dissimilar* inclusions, even if *non-limiting***.

4. **No more than 15% of the area can be can be *dissimilar limiting* inclusions**.

5. **No single dissimilar limiting inclusion can exceed 10% of the area**.

In the USA **undifferentiated groups are commonly used for very steep or stony phases**, so that there is only one legend category of these. Problem: for some uses (e.g. quarrying) the difference in parent material might be important. They should be used sparingly, if at all. Much of the motivation for undifferentiated groups came from the desire to have a smaller number of legend categories, and hence thinner soil survey reports and less work for the correlator. But with modern information technology this becomes less important

The use of undifferentiated groups makes correlation among different survey areas more difficult.

> Following the NY State example above, if the Broome County survey is now correlated to the Tioga County survey (adjoins Broome Co. on the west), where Lackawanna soils do not occur, we would see delineations of 'Bath' (in Tioga Co.) correlate across the county boundary with 'Bath and Lackawanna'. If we correlate to the Delaware County survey (adjoins Broome Co. on the east), where Bath soils do not occur, we would see delineations of 'Lackawanna' (in Delaware Co.) correlate across the county boundary with 'Bath and Lackawanna'. Now, if we want to make a unified 3-county survey (e.g. to create a uniform state-wide database), we must re-correlate the Bath consociation (Tioga Co.) and the Lackawanna consociation (Delaware Co.) to the undifferentiated group 'Bath and Lackawanna' (Broome Co.), thereby losing information! It would have been better to map the Bath and Lackawanna separately in Broome County; then consociations would have correlated across the whole area.
>
> A final note about this example: both series are in the same ST Family, so if the categorical level were from the beginning ST Family, all three counties would have the same consociation.

Naming undifferentiated groups

These are named by the constituents, using the word **'and'**, e.g. 'Bath and Lackawanna channery silt loams'. (Note: a 'channer' is an upstate NY folk name for a long thin sandstone or massive shale fragment, it has been adopted by the Soil Survey Manual).

My opinion is that in this case it is better to use two consociations: Bath and Lackawanna.

4.1.3 Compound map units

If the map unit fails the test for both types of homogeneous map units (consociations and undifferentiated groups), it is a **compound map unit**, where **more than one soil must be named** explicitly.

We divide first of all according to whether the different soils in the map unit occur in a 'known and definite pattern' on the landscape, that is, known to the surveyor. This does not mean that the surveyor can map them at the mapping scale, only that the pattern is known.

4.1.3.1 Unassociated soils

In the case where the components of a map unit do not all occur in every delineation, or if we don't even know if the soils always occur together, and in addition the components do not have similar interpretations, we must use the map unit type 'unassociated soils'. What we are admitting with this name is that the map user may find any or all of the named soils in any delineation, and that the different soils will have different properties and management.

This is usually a **bad idea** and in general indicates that **the surveyor does not understand the landscape** and therefore has created a single map unit out of a incorrect set of delineations**.** However, in some complex landscapes, or with **insufficient sampling**, this may in fact be the surveyor's true state of knowledge. In these cases, it is more honest to use the 'unassociated soils' map unit rather than one of the two that follow.

Naming unassociated soils

Name the soils we may find in delineations of the map unit, using the conjunction 'or', adding soils to the map unit name until the homogeneity criteria are met, using all the named soils to meet them.

Example: 'Norfolk or Lynchburg soils'. This means that we can find either of these soils in any delineation, and we have no idea about the pattern within delineations.

4.1.3.2 Associations

If the major (contrasting) soils and their pattern is known, and **this pattern is similar in every delineation of the map unit**, we then divide into those map units which could be mapped as homogeneous map units at 'reasonable' scales (these are the **associations**) and those where the soil pattern is so intricate that they could not be so mapped (these are the **complexes**).

> Associations: components could be mapped separately at a larger scale

> Complexes: components could *not* be mapped separately at a larger scale

What do we mean by 'reasonable' scales? In practice, an arbitrary scale (1:24 000 according to the 1993 Soil Survey Manual) is accepted as the largest practical scale. In other words, if the constituents couldn't be mapped consistently at that scale, then the compound map unit is a complex. Thus the components of an association would have to be at least the size of the MLA at 1:24 000, i.e. 2.3ha. However, in the USA many soil maps are now being made at 1:12 000 (MLA 0.6ha), so perhaps this criterion will be changed.

> **SSM**: Associations are compound map units of two or more soils that could be separately mapped as consociations at scales of 1:24 000 (1:12 000?) or larger

This is somewhat illogical, as it confuses map scale with soil pattern. Perhaps the complexes should be defined as soil patterns that are **not mappable at any reasonable scale** and would have to be mapped by exhaustive sampling and interpolation.

My definition: An **association** is a map unit at a given scale, where contrasting soils or land types occurs in **regular**, **predictable**, and **mappable** pattern **at some practical larger scale**. In addition, **all components must occur in approximately the same proportions in all delineations of the map unit**. By 'mappable' I mean that there are consistent external features (geomorphology, vegetation, land use, surface properties and topography…) to assist in delineation.

> Definition: Associations can be separately mapped, based on external features, at some larger (realistic) scale; specify that scale to the map user (e.g., 'association, mappable at 1:12 000')

A good test of whether a map unit is an association or not is if you can make a **diagram** of a typical delineation, showing the **pattern** of the constituents and how you can find them in the field. The field expression can be a landscape relation or simply a visual cue. **Catenas** (toposequences) are usually associations, with boundaries that can be inferred in the field or on a photo from hillslope position and surface wetness or color.

Examples:

1. A hillside catena with a linear dimension of 300m down slope, with three soils corresponding to the hilltop & shoulder, side slope, and footslope positions. These can be seen and delimited on the airphoto. However, if the width of each soil body on the transect is 100m, this can not be shown at any scale smaller than 1:50 000 (100m_g = 2mm_map minimum delineation width). This is a typical example in many landscapes, and shows why 1:25 000 scale maps often show consociations and 1:100 000 scale maps rarely do.

2. Wet spots ('potholes') in small basins of 200m² in an intricate pattern, between small hills, with a recurrence distance of 100m (i.e., potholes on more or less a 100m grid). A well-drained soil is on the small hills and a poorly-drained soil in the potholes. These can easily be seen in the field and on the airphoto. They could be delineated on a 1:2 250 scale map, corresponding to a MLA of 200m². They can not be delineated at even 1:5 000. By the SSM, these are complexes; I consider them associations, albeit only at a very detailed mapping scale.

Associations are very often used for soil maps at semi-detailed or smaller scales, and for generalizations of larger-scale maps.

How to name associations

Associations are named by their major soils (enough to meet the homogeneity criteria for a consociation, but the soils taken together), **the names separated by a hyphen** '-' and with the word 'association', e.g. 'Norfolk-Goldsboro loamy sands, 0-2% slopes, association'. **Soils are named in order of area covered within the map unit**, including with each soil any similar inclusions.

> A typical **example** is from the detailed soil survey of Cayuga County, NY, USA. The association is a drainage association of heavy-textured soils on recent lacustrine sediments: the imperfectly-drained Schoharie silt loam, the somewhat poorly drained Odessa silt loam, and the poorly drained Lakemont silty clay loam. These soils and their taxadjuncts occupy about 40, 30 and 20% of the area. Also included in this association are about 10% topographically-higher areas of fine-textured glacial till that were not covered by lacustrine sediments; these are the Cazenovia silt loams. Within a typical 100ha area all four are present, in a predictable and recognizable pattern. Here the diagram can show the landscape position, which is directly related to the drainage class, and easily observable in the field or on airphotos. A semi-detailed map at 1:100 000 has a MLD of 40ha, so can't show these soils separately, however they can be shown as an association.
>
> So, the name of this map unit is 'Schoharie-Odessa-Lakemont association'; it has one dissimilar inclusion: 10% Cazenovia. This differs from all the other soils because it has no lacustrine material, only glacial till; also it is well-drained (although in that respect it is similar to Schoharie, which is imperfectly drained).

Once a component is listed in the association name, it is no longer an inclusion. The purity of the association is the sum of the purities of the components. In particular, if there are similar soils, they are grouped with the named component that they most resemble.

4.1.3.3 Complexes

Map units that fail the test of an association only because the components can not be separately mapped are called **complexes**. But, all components must occur in approximately the same proportions in all delineations of the map unit; otherwise these would be unassociated soils. Also, the components must be contrasting, otherwise they could be grouped together in a consociation.

<u>How to name complexes</u>

Complexes are named by their major soils (enough to meet the homogeneity criteria for a consociation, but the soils taken together), the names separated by a hyphen '-' and with the word 'complex', e.g. 'Methwold-Newmarket-Worlington complex' (from Figure 17 in [1]). Soils are named in order of area covered within the map unit.

> An **example** would be the East Anglian fenlands (see Dent & Young [24] Plate 1) *before* drainage exhumed the pattern. The sandy channels were buried too deep to be seen on airphotos, and were covered by peat to 1m or so, and couldn't be seen on the surface either. They could be identified only by exhaustive boring to >1m and even then the borings would have to be spaced every 10m or finer to catch the smaller channels. Yet by sampling it was known that ≈ 20% of the map unit had buried sandy channel deposits below 1m; this is obviously a different soil. So a complex of two soils would have been the correct map unit *at any scale*.

4.1.4 Key to map unit types

Key words: delineation, map unit, components, taxon, similar & dissimilar taxa, taxadjunct (see §4.3.1, below; only applies to soil series of Soil Taxonomy), dominant component, mappable

Do all delineations of the map unit have the same components, in similar proportions?
.. 1.**Yes**. Consider the taxon of the dominant component (i.e. the one which occupies the most area)
.. ...≥75% in the taxon, similar taxa, or their taxadjuncts?
.. .. 1.1 **Yes**
.. ..<15% dis-similar, limiting with respect to the taxon?
.. .. 1.1.1 **Yes**
.. .. <10% any single dis-similar, limiting w.r.t. the taxon?
.. ..1.1.1.1 **Yes**
.. .. ≥50% in the taxon or its taxadjuncts?
.. .. 1.1.1.1.1 **Yes** ⇒ **Consociation** of the dominant taxon
.. .. 1.1.1.1.2 **No**
.. ..≥3 similar components (including the dominant component)?
.. .. 1.1.1.1.1.1 **Yes** ⇒ **Consociation** of the dominant taxon
.. .. 1.1.1.1.1.2 **No**: GoTo 1.2
.. ..1.1.1.2 **No**: GoTo 1.2
.. .. 1.1.2 **No**: GoTo 1.2
.. .. 1.2 **No**. Group the components by similarity
.. ..Do the components occur in a **regular**, **mappable** pattern at a practical larger scale?
.. .. 1.2.1 **Yes** ⇒ **Association** of the main components grouped by similarity
.. .. 1.2.2 **No** ⇒ **Complex** of the main components grouped by similarity
.. 2. **No**
.. ... Do all delineations of the map unit have almost identical interpretations for all land uses?
.. .. 2.1 **Yes** ⇒ **Undifferentiated group**
.. .. 2.2 **No**
.. ..Do delineations separately meet the criteria for a consociation of their 1st components?
.. .. 2.2.1 **Yes** ⇒ Create several map units and assign delineations to these map units
.. .. 2.2.2 **No** ⇒ **Unassociated soils**
.. 3. **Don't know** ⇒ **Unassociated soils**

4.2 Map units classified by their categorical level

For area-class soil maps, we must group point observations and/or separate the landscape continuum into segments (map units), and describe the contents of the segments.

4.2.1 What's in a name?

<u>Option 1: Local names by direct observation</u>

One alternative is to separate 'similar' soils by direct observation, and give them local names (if these match with our observations), or even arbitrary names, like 'Soil A', 'Soil B', etc. We would group observations into locally-meaningful classes. This requires careful correlation of different observations, to make sure that we haven't created false classes. The techniques of multivariate ordination are applicable here, if there is enough data [61, Ch. 8].

Option 2: Characteristics by direct observation

Or, we could name the map units directly by their characteristics: 'shallow, sticky clay soils…'. In this case there is **no attempt at correlation nor at creating legend categories**! Instead, each delineation (typically a 'natural' landscape unit) is described directly.

The characteristics are typically from a standard set, e.g.:

1. Epipedon type: { Mollic, Ochric (thin Mollic), Ochric (not Mollic) }
2. Topsoil particle-size class: { very fine, fine, fine-loamy, …, sandy }
3. Subsoil particle-size class: { very fine, fine, fine-loamy, …, sandy }
4. Depth to texture change: { 0 = no change, 1 = <20cm, 2 = 20-40cm… }
5. Current erosion / truncation{ 0 = none, 1 = slight, … }

and so forth. The obvious **problems** with this approach are:

1. The number of significant characteristic is large, so the delineation symbol is awkward
2. There is no concept of a natural soil body where these characteristics occur together (co-vary). For example, Ochric epipedons could always be associated with shallow soils on steep slopes in the study area. Only by looking at every delineation would we discover this.

In fact, the concept of **series** (see §4.3) can be thought of as a **shorthand** for specific combinations of properties.

Option 3: Land Qualities by direct observation

Similarly, we could name the map unit directly by its land qualities: 'high water-holding capacity, low erodibility, easy workability…'. This requires that the surveyor interpret, not just map, and is probably too difficult for routine mapping.

Option 4: Names within a classification system

In general **we use names with wide acceptance and a more-or-less precise definition**. This has three purposes:

1. It makes *local naming* easier, because much of the work in defining classes has already been done (but does it fit our area?)
2. It makes *interpretation* easier, because the named soil occurs elsewhere, and we can use experimental results, existing interpretations, or experience from a wider area to make predictions for the present survey area.
3. It makes possible the *correlation* with other mapped areas, leading to *unified surveys* and *databases*.

4.2.2 Taxonomic units vs. map units

A **taxonomic classification** groups **individuals**; a **map unit** is a **geographical association**. ST's limits are defined to group 'similar' individuals; a map unit's limits are in practice defined geographically. To what extent can these be matched?

One critic of the use of taxonomic units for mapping was Butler [15], who said:

> "…unless the classes [of the classification system] roughly correspond to the natural modalities of the survey area, and at least roughly conform to the more obvious discontinuities in the landscape, they may be difficult to map and require the subdivision of areas that common sense [and interpretations] requires to be undivided".

It would be very strange for a land user to see a soil boundary dividing what is clearly a 'homogeneous' landscape and soil unit, from the point of view of all reasonable land uses. And in fact it would be very hard to find such a boundary accurately.

The Americans [48, p. 21] now admit:

> "When the limits of soil taxa are superimposed on the pattern of soil in nature, areas of taxonomic classes rarely, if ever, coincide precisely with mappable areas."

One way around this problem is to accept a so-called **hiatus** between the classification system and the map units, and establish norms for relating the classification system and the 'natural' soil bodies, as we will see. Another way is to establish 'taxadjuncts' (see below). In practice, if the taxonomic system has been designed from wide field experience, the discordance between taxonomic and natural map units will be as small as possible (this in fact is how Soil Taxonomy was developed).

4.2.3 Soil Taxonomy as a mapping legend

One alternative is to use Soil Taxonomy directly as a mapping legend, in other words, the names of map units come directly from ST, and follow the rules of the SSM to designate their composition. To understand why this might be a good alternative, we should first understand some facts about ST.

4.2.3.1 Some facts about Soil Taxonomy

Original reference is [49], the 'Big Green Book'. Since then several amended keys have been published; the Green Book is to be re-issued with all these updates in early 1999.

1. Soil Taxonomy was explicitly designed to **support** soil survey operations in the USA, specifically **correlation** and grouping of soil series. But, it was ***not*** designed as a ready-made mapping legend; in the USA almost all mapping uses 'mapping series' which are correlated to ST.

2. In use it is a **deductive** system, i.e. we classify pedons according to a ready-made key with 'strict' class limits (actually, there are some deliberate ambiguities…)

3. But, it was created, and is revised, as a **synthetic** system, i.e. it is an attempt to **group similar soils** at appropriate levels. The closer the relation between soils, the further down the system they are split. Thus, it summarizes much intensive work, mostly in the USA but increasingly from other countries, on important soil differences. In this sense it can save the observer a lot of work, in that it is a ready-made catalog of important soil properties, based on extensive field observation and laboratory data.

4. ST is a **hierarchical classification system**, i.e. once a soil is placed in a higher category, it stays there, and is further classified. **Levels**: (1) Order, (2) Suborder, (3) Great Group, (4) Subgroup, (5) Family, (6) Series. From this we see that even the Series is considered as part of the system, and in fact it was an explicit requirement in the development of the system that series be the lowest level in the hierarchy.

5. A given soil characteristic can appear at any hierarchical level, depending on its perceived importance. Example: soil moisture regime can be at the Order (e.g. Aridisols), Suborder (e.g. Udults), Great group (e.g. Udipsamments) or subgroup (e.g. Ustic Quartzipsamments) levels, or not at all (e.g. Haplofibrists can be udic or ustic).

6. A given soil characteristic often does not appear in the name, but is only implied by the way that the keys are constructed, i.e. the questions that had to be answered in order to arrive at a particular classification.

4.2.3.2 Should Soil Taxonomy be used as a mapping legend?

Since the 3rd revision of the Keys to Soil Taxonomy (1988), in theory any soil individual can be classified to family level in Soil Taxonomy, i.e. all pedons should ‘key out’ to family level. So, since every soil can be classified, can’t we just use ST directly as a ready-made legend?

Yes

Some reasons why this is a good idea:

1. The system was designed to support soil survey in USA, and has received important contributions from other countries. It synthesizes many important differences at appropriate levels of classification, so saves the soil scientist a lot of work trying to ‘re-invent the wheel’. **The limits in ST are important limits for interpretation**.

2. A large part of the ‘Correlation’ problem is reduced to ‘correct classification’ (still, we need to determine the composition of map units and assign correct names).

3. It may be impractical to set up Series, let alone a local classification system, in a short time, so if we use a ready-made system, we get an ‘instant legend’.

4. There is a well-developed methodology (the ‘ITC Geopedological Approach’) that is widely-used in reconnaissance and semi-detailed soil survey, and also by many national soil survey organizations, that uses ST to name map units.

No

Some reasons why this is *not* a good idea:

1. May not include all the soils, esp. in tropics, or for areas with combinations of soil-forming factors not found during the development of Soil Taxonomy. Examples are tropical peats and many anthrosols. Before earlier revisions there were inadequate treatment of Andosols and frozen soils. Actually these soils are ‘included’ in that they can be classified, but they won’t be separated from different soils.

2. May make distinctions at the wrong categorical level for an area. I.e. very important differences come at a low level in the system.

 Example: abrupt textural changes (so-called ‘duplex’ soils) only at the series level, when they may control land use in some areas.

 Example: no Gleysols, which in some areas may be the highest categorical (conceptual) level of soil differences.

 Example: Starting with 8th edition, there are no more Umbrepts, which are important acid, carbon-rich soils. They are now recongized at a lower level ,as Humic Dystrudepts.

 Example: [Nordt, 1991 #951Paleustalfs can have abrupt textural changes, or just a thick argillic horizon but with a gradual textural change. There are major differences in water relations, yet in a map of great groups the two types would be together in a consociation.

3. May not make important distinctions at all. Example: Netherlands: susceptibility to permanent compaction; stages of ripening in polder reclamation… Of course, these can always be used to establish series, but one would expect that such important differences would be reflected at higher categorical levels.

4. May make correct distinctions but with diagnostic criteria that are not optimal for an area. E.g. 35% and 50% base saturation, where the natural limits separating important groups in an area may be centered on 30% and 60%.

4.2.3.3 Increasing categorical detail by level

All levels of **Soil Taxonomy** can be used depending on the scale of the map and the available information; increasingly-specific information is used at lower levels.

Some **Orders** have reasonably specific interpretation:

Histosols: primarily organic matter
Vertisols: shrinking and swelling clays
Gelisols: permanently frozen

Some other Orders have some interpretive value, but with more differences within the Order:

Alfisols: high base-saturation soils with textural contrast (heavier subsoils)
Ultisols: low base-saturation soils with textural contrast (heavier subsoils)
Oxisols, **Andisols**: specific mineralogy and physical properties
Mollisols: high base-saturation, high organic matter, ‘soft’ thick dark surface horizons
Spodosols: coarse-textured, acid, iron-aluminum-organic matter complexes

And, some Orders have very little interpretive value:

Entisols
Inceptisols
Aridisols

Suborders indicate some major characteristics, e.g. soil climate (Udults vs. Ustults), drainage (Aqults vs. Udults), major characteristic influencing soil properties (Salids, Calcids, …), major reason for classification in an Order (Psamments, Fluvents,…) Some of these properties are directly important for interpretations.

Great Groups: bring in other important soil properties, e.g. ‘Fragi’Udepts vs. ‘Dystr’Udepts (without Fragipans, low base saturation) vs. ‘Eutr’Udrepts (high base saturation). But see the example of Paleustalfs, above.

Suborders: indicate intergrades to other taxa, e.g. ‘Vertic’ subgroups; drainage intergrades ‘Aquic’, ‘Aeric’, etc., as well as internal properties: e.g., ‘Lithic’, ‘Abruptic’.

Families: many interpretations are possible here. Includes moisture & temperature regime, general particle-size class including a general idea of coarse fragments in the profile, clay mineralogy including activity of the clays.

4.2.3.4 Correspondence between taxonomic level of map legend & map scale

ST was designed to support this rough correspondence. In some areas it works well, but often there is little correspondence.

Approximate correspondence: Series 1:20k, Family 1:50k, Subgroup 1:100k; Great Group 1:250k.

But this is not often true! A single detailed delineation can easily include several Orders. Or, a delineation on a small-scale map may only contain a small proportion of the total allowed variation in a higher taxonomic level.

4.2.4 World Reference Base as a mapping legend

The “World Reference Base for Soil Classification” (abbreviation **WRB**) is the international standard soil classification system, accepted as such as the 16th World Congress of Soil Science in Montpellier (1998) [8, 23, 30]. It was developed by an international collaboration coordinated by the International Soil Reference and Information Centre (ISRIC) and sponsored by the International Union of Soil Science (IUSS) and the FAO via its Land & Water Development division.

> “A world reference system for soil resources is a tool for the identification of pedological structures and their significance. It serves as a basic language in soil science and facilitates (1) the scientific communication; (2) the implementation of soil inventories and transfer of pedological data, elaboration of different systems of classification having a common base, interpretation of maps, etc.; (3) the international use of pedological data, not only by soil scientists but also by other users of soil and land.”

It was not designed to directly support soil mapping; rather, it should be used to correlate central concepts of locally-defined soil classes. However, as with ST, the WRB provides a ready-made reference to large numbers of important soil properties, and we may think about using it directly as (part of) a mapping legend.

4.2.4.1 Structure of the WRB

The WRB is a two-level classification:

At the **first (top) level**, there are **30 Reference Soil Groups**. Examples: Histols, Fluvisols, Luvisols. These represent groupings of soil individuals that are the result of major soil-forming processes, and as such have broadly-similar behaviour. These roughly correspond to the **suborders** (2^{nd} level) **of Soil Taxonomy** (see below).

At the **second (bottom) level**, there are subdivisions of each Reference Soil Groups, using any defined combination of 121 qualifiers. Examples: Leptic Umbrisols, Chromi-Vertic Luvisols. It is possible to use either a single qualifier (the most important) or all relevant qualifiers. These second-level groups show more specific properties within reference groups. These roughly correspond to the **subgroups** (4^{th} level) **of Soil Taxonomy** (see below).

These two levels are not comprehensive: they do not include all the **internal soil properties** or **site properties** that characterise map units in detailed mapping:

(1) Some **detailed internal properties** are **not considered** at this level of detail, namely, substratum layers, thickness and morphology of solum or individual horizons. These can be used to define **families**, **series** or **forms** locally, for **detailed soil survey**.

(2) The second level does not take into account many **site factors** that are important differences among soil map units. In particular: climate, parent material, vegetation, depth of water table or drainage, and physiographic features such as slope, geomorphology or erosion are not considered as such, except insofar as they have affected soil morphology. These features can be used locally to defined **mapping phases**, but they are not considered soil properties to be classified as such.

4.2.4.2 Use of WRB in naming map units

At **high categorical levels**, WRB names can be used directly.

At **low categorical levels**, WRB names must be supplemented with more specific information, either as **families** or **series**, as well as site information as **mapping phases**.

A reasonable idea is to use the **family criteria of Soil Taxonomy** directly as a 3^{rd} level in WRB names, including also the **soil moisture regime**, which is almost always implied by the ST classification to subgroup. The keys to families in KST must be adjusted for WRB names, since they sometimes refer to higher levels of KST.

These families can then be used to group mapping **series**.

4.3 The Soil Series

In detailed soil mapping, and on the landscape itself, the continuum of soil characteristics is divided into more-or-less natural **soil series**. This is a controversial and at times confusing term, with a long and complex history, as well as important differences in usage between countries. We will only study two modern concepts of the soil series: a common-sense definition (Dent & Young) and the formal definition of the USDA (Soil Taxonomy and the Soil Survey Manual).

According to Dent & Young, [24, p. 82]:

> “[The soil series] is conceived as **a grouping of soils which are alike in their characteristics and behavior in the landscape**. Soils within a series are **developed on the same parent material in the same environment** and have **profiles that are almost alike**, with **horizons that are similar in their vertical sequence, thickness and morphological properties**.
> ...
> “Each series is intended to have a unique combination of **site features** and **morphological characteristics** which **can be assessed, for the most part, in the field.**
> ...
> “Once a series has been defined and mapped according to its differentiating characteristics, **many accessory properties of practical importance can be predicted**.”

Note that the emphasis is on a **recognizable field unit** that can serve as an **information carrier** for **interpretations**.

According to the Soil Science Society of America’s Glossary [47]:

> “**Soil series**: The **lowest category of U.S. system of soil taxonomy**; a conceptualized class of soil bodies (polypedons) that have limits and ranges **more restrictive than all higher taxa**. Soil series are commonly used to name dominant or co-dominant polypedons represented on detailed soil maps. **The soil series serve as a major vehicle to transfer soil information and research knowledge from one soil area to another.**”

Again, the emphasis is on **technology transfer**. The series is so tightly (narrowly) defined that definite, specific statements about use and response to management can be made. But there is a major difference between the Dent & Young and the SSSA definitions: the first is bottom-up and the second top-down, i.e. **according to the USDA, the Series is part of Soil Taxonomy**.

This concept of Series is amplified in the Soil Survey Manual [48]:

> “The soil series category is the most **homogeneous category in the taxonomy** used in the United States. As a class, a series is a group of soils or polypedons that have horizons similar in arrangement and in differentiating characteristics. The soils of a series have a **relatively narrow range in sets of properties**. The surface layer and such features as slope, stoniness, degree of erosion, and topographic position may vary unless these factors are associated with significant differences in the arrangement of horizons.
>
> Soil series are **differentiated on all the differentia of the higher categories plus those additional and significant characteristics in the series control section**. Some of the characteristics commonly used to differentiate series are the kind, thickness, and arrangement of horizons and their structure, color, texture, reaction, consistence, content of carbonates and other salts, content of humus, content of rock fragments, and mineralogical composition. A significant difference in any one of these can be the basis for recognizing a different series. Very rarely, however, do two soil series differ in just one of these characteristics. Most characteristics are related, and generally several change together.”

Note the insistence that the Series be the lowest categorical level of Soil Taxonomy. Many authors and especially mappers have criticized this as being unrealistic. Also note the explicit exclusion of important properties (surface layer, slope, stoniness…) from the definition; these are included in the concept of the phase (see below).

Historical concept of the soil series (supplementary information)

> The earliest soil maps were essentially of surficial geology, mainly quaternary deposits and products of rock weathering. The Series was conceived as a horizon sequence in a broadly defined parent material, and could have a very wide textural range, as long as the parent material was broadly similar, e.g. 'old marine sediments'. Fairly soon the textural range was tightened, so that a Series had a narrowly-defined parent material (e.g., loamy, calcareous marine sediments) and a similar horizon sequence, which was taken to indicate the kind and degree of pedogenesis. At the same time came the concept that each Series occurs on a characteristic landscape position as well as on a characteristic parent material. Still, class limits were quite wide, and often the Series was too broad to interpret with sufficient precision for many land uses. (The soil 'type' was used for a while, with interpretive precision quite similar to the modern series.) Slowly the idea developed that **the Series is first and foremost an information carrier to the public**; in the USA the series names became known and were even used in advertisements for farm sales. They also became used by the agricultural extensionists and commercial advisors. Then with the development of Soil Taxonomy, the Series became much more tightly defined (since it had to respect all the higher levels). Many well-established Series were split, e.g. by temperature regime lines, family particle-size class, depth limits in the soil & to bedrock, etc. Some of these splits were good from an interpretive viewpoint and just required recorrelation of existing surveys; others created several Series that were difficult to separate in mapping, because the limits forced by ST were often exceeded in 'homogeneous' natural soil bodies.

4.3.1 The taxadjunct

Note: This section applies only to Soil Taxonomy

The concept of '**taxadjunct**' applies only to the **soil Series** defined as the lowest categorical level of **Soil Taxonomy**. Otherwise the concept has no meaning, because higher levels in Soil Taxonomy can classify all pedons, whereas there may be pedons that do not fit in the definition of any established Series.

To get around the insistence on series being part of Soil Taxonomy, the Americans were forced to invent the so-called **taxadjunct**, which is defined by the SSM [48. p. 21] as follows:

> "**Taxadjuncts** are polypedons [or pedons] that have properties outside the range of any recognized series and are **outside higher category class limits** by one or more differentiating characteristics of the series. **The differences in properties are small so that major interpretations are not affected**. A taxadjunct is given the name of an established series that is most similar in characteristics. It is an adjunct to, but not part of, the named series. **It is treated as if it were a member of the named series**, and its interpretations are similar to those for comparable phases of the series for which it is named. The difference from the established series is described.
>
> "Example: A potential series is in a fine-silty family particle size class, marginal to fine-loamy; however, it differs from an established fine-loamy series in only particle size and no appropriate fine-silty series has been identified. The potential series is given the name of the established series, and a new series is not proposed."

To repeat the crucial points:

1. A taxadjunct pedon is outside the **Series** limits by one or more diagnostic criteria listed in the Official Series Description. This is very often because of…

2. A taxadjunct pedon is outside the limits of some **higher level in Soil Taxonomy** (Order, Suborder,…family), by one or more diagnostic criteria; however,

3. The nature and arrangement of horizons is similar; in particular, the taxadjunct pedon **shares a diagnostic limit** with the Series at some higher level in Soil Taxonomy.

4. The landscape relations and other genetic factors are similar;

5. The interpretations are identical;

Note the phrase 'outside higher category class limits …'; this implies that **a pedon in the same family as an established Series can not be a taxadjunct**. What to do in this case? According to the National Soil Survey Handbook §627.06 [51]:

> "If a soil is correlated that has properties that are slightly outside the official series range but is in the same family as the official series, it is not recognized as a taxadjunct. In this case, one of two alternative actions is taken:
>
> (1) the official series range is widened to include the soil as correlated, or
>
> (2) a statement is placed in the final correlation memorandum to explain how the soil differs from the official series and why the official series was not revised to include the aberrant property or properties."

Example of a taxadjunct:

> Differentiating characteristics even at the Order level can cause taxadjuncts. Consider a pedon that would qualify as a fine, mixed, thermic Typic Haplud**ult** (e.g., the Cullen series from the North Carolina piedmont) except that the base saturation in the argillic horizon is slightly >35%. Then this pedon qualifies as an fine, mixed, thermic **Ultic** Haplud**alf** (e.g., Mecklenburg series) (Ultic subgroup: must have 35-60% base saturation; these are used for Alfisols with base saturation <60%, i.e. transitional to Ultisols). If the Series (in this case, Cullen) is defined with a base saturation range of 25-35% (i.e., an Ultisol marginal to Alfisol), pedons in the 35-40% range could be defined as a taxadjunct to this series. Or, if the Mecklenburg series is restricted to base saturations of 35-45% (i.e., an Alfisol transitional to an Ultisol), pedons that otherwise would qualify as Cullen could be considered taxadjuncts to the Mecklenburg series. In the current situation, both series have been defined, so they are considered 'similar', not 'taxadjuncts'.

What is going on here is that the **natural series have been forced into too small a range by the higher categories of Soil Taxonomy**. The taxadjunct acts like the Series, looks like the Series…but it doesn't fit in the Series, because of the 'straight jacket' of Soil Taxonomy.

In fact, the 'natural' series (see next §) often has a fairly narrow range of variation which doesn't respect the limits of Soil Taxonomy (family level or higher). In the example above: the natural range of the Cullen series could be 25-40% base saturation, and the central concept could be correlated to the family with the typical interpretation, in this case the Typic Hapludult.

This also 'solves' the problem of soils in transitional areas between moisture and temperature regimes. A series in a Thermic family can have taxadjuncts in Mesic families, as long as the soil is otherwise similar, and the soil temperature is 'borderline' to mesic.

So, in practice, the correlator classifies the **central concept** (typifying pedon, either representative or synthetic) of the 'natural' series, writes the series description to include as much variation as will fit within Soil Taxonomy, and then the rest of the natural variation is a taxadjunct.

Now, when a series of Soil Taxonomy (or one of its phases) is used in a **map unit name**, we can consider pedons of the taxadjunct **as if they were part of the series**, for purposes of computing required purity (e.g. ≥50% of a consociation in the named taxon). This just repairs the damage done to the original concept of the mapping series by the insistence that the series be the lowest level of Soil Taxonomy.

> Example: If a map unit is estimated to consist of 40% Cullen pedons, 40% Mecklenburg pedons (slightly higher base saturation), 20% pedons in similar taxa; this map unit should be called 'Cullen soils' (a consociation of one series **and its taxadjuncts**). Note that if we used families in this case, we would be forced to call such a map unit a complex! i.e. 'fine, mixed, thermic Typic Hapludult – Ultic Hapludalf complex'. This is an absurdity forced on us by the rigid limits in Soil Taxonomy.

4.3.2 Four views of soil series

The following views of soil series in practice converge to similar definitions.

<u>A natural entity resulting from a unique set of circumstances</u>

Although the soil cover is a continuum, not all combinations of characteristics are found. Instead, a unique set of soil-forming factors should result in a soil with the same characteristics, within some tolerance. It is impossible to discuss each point separately, so we group them into 'natural' classes whose limits are set by the soil-forming processes.

This is really the **key hypothesis** of soil survey; the soil series is the most detailed expression of this hypothesis. The challenge in soil classification and mapping at the detailed level is to find these 'natural' series, describe them, and map them.

<u>A natural cartographic entity at detailed scales</u>

If the hypothesis is correct, and in addition soil-forming factors have some spatial coherence (auto-correlation), we expect adjacent soils to be similar. Thus all pedons in some local polypedon will have characteristics within a fairly narrow range; this is the **mapping series**.

<u>The basic unit of information transfer</u>

The practical reason why soil series are so important is that they are the finest classification that is generally useful to group experiences. Also they form natural polygons, as in the previous view.

The series is sometimes called the basic **information carrier**.

<u>The lowest category in a classification system</u>

In a hierarchical classification of soils, the finest level that can be practically defined; see above for the definition in Soil Taxonomy.

4.3.3 Information about Soil Series

The Series is characterized by specific information.

General information

First, there is a general statement about the concept of this series: parent material, physiographic position, main soil-forming factors, and general limits on important properties. For example, from the Official Series Description of the Norfolk series:

> “The Norfolk series consists of very deep, well drained, moderately permeable soils that formed in loamy marine sediments of the Coastal Plains. These upland soils have slopes ranging from 0 to 10%. Near the type location the mean annual temperature is 16°C., and the mean annual precipitation is approximately 1250mm.”

Taxonomic classification

Then, there is its classification in a standard system, e.g. Soil Taxonomy:

> “TAXONOMIC CLASS: Fine-loamy, kaolinitic, thermic Typic Kandiudults”

Note that all pedons classified in the Norfolk series are supposed to fit in this family! In practice, many pedons mapped with Norfolk and quite similar to it will be in other taxonomic families; these are then Norfolk taxadjuncts.

Central concept: the modal or representative profile

The series should have a **central concept** of the ‘typical’ pedon; this is used by the surveyor and land user alike to reduce complexity. Often modelers use this central concept to represent the entire mapped area. And if we believe that specific combinations of soil-forming factors lead to specific soil properties, and that certain combinations of soil-forming factors are ‘typical’ in a certain landscape, we believe in the ‘typical’ result.

So, this represents the Platonic ideal of the Series: the ‘typical’ individual. This is like any ‘typical’ individual: it may not exist! (cf. the ‘typical Dutchman’) even though we have a very clear idea (the ‘ideal’) about it.

The ‘modal profile’ can be **synthetic**, i.e. it combines actual observations according to the surveyor’s experience and information on the series in a database. This has been done to provide uniform datasets for regional modeling, e.g. for the EPIC erosion-productivity model [63] applied to much of the USA.

But, in some descriptions an actual **representative** profile, called a **typifying pedon**, is selected to represent the series. Presumably this was selected by experienced correlators as a good example of the series. This in fact was done for the Norfolk series:

TYPICAL PEDON: Norfolk loamy sand--cultivated. (Colors are for moist soil unless otherwise stated.)

Ap--0 to 23cm; grayish brown (10YR 5/2) loamy sand; weak fine and medium granular structure; very friable; few fine and medium roots; some darker-colored material in old root channels; strongly acid; clear smooth boundary. (7.5 to 25cm thick)

E—23 to 36cm; light yellowish brown (10YR 6/4) loamy sand; weak medium granular structure; very friable; few fine and medium roots; some darker-colored material in old root channels; strongly acid; clear smooth boundary. (0 to 25cm thick)

Bt1--36 to 43cm; yellowish brown (10YR 5/6) sandy loam; weak medium subangular blocky structure; friable; few fine and medium roots; strongly acid; clear wavy boundary.

Bt2--43 to 97cm; yellowish brown (10YR 5/6) sandy clay loam; weak medium subangular blocky structure; friable; many fine and medium pores; few faint clay films on faces of peds; strongly acid; gradual wavy boundary.

Bt3--97 to 147cm; yellowish brown (10YR 5/6) sandy clay loam; few fine faint soft masses of iron accumulation of strong brown, pale brown, and yellowish red; weak medium subangular blocky structure; friable; few faint clay films on faces of peds; strongly acid; gradual wavy boundary.

Bt4--147 to 178cm; yellowish brown (10YR 5/6) sandy clay loam; common medium distinct yellowish red (5YR 5/8) soft masses of iron accumulation, pale brown (10YR 6/3) and light brownish gray (10YR 6/2) iron depletions; weak medium subangular blocky structure; friable; few firm yellowish red plinthite nodules; strongly acid; gradual wavy boundary. (Combined thickness of Bt horizon is 100 to more than 150 cm)

BC--178 to 208cm; mottled brownish yellow (10YR 6/6), strong brown (7.5YR 5/6), yellowish red (5YR 5/6) sandy clay loam; weak medium subangular blocky structure; friable; approximately 5 percent firm, brittle nodules of plinthite; strongly acid; gradual wavy boundary. (17.5 to 37.5cm thick)

C--208 to 254cm; mottled red (2.5YR 4/8), strong brown (7.5YR 5/8), brownish yellow (10YR 6/8), and gray (10YR 5/1) sandy clay loam; massive; friable; strongly acid.

TYPE LOCATION: Robeson County, North Carolina; 1 1/4 miles south of Parkton; 300 feet west of State Road 1724 and 60 feet south of farm road.

Range of properties

Clearly, the various pedons of the series are not identical. So, the Series is defined with its **allowable range** of diagnostic properties. For example, from the Norfolk OSD:

> "Solum thickness is more than 150cm. Few to about 5% small rounded siliceous pebbles are on the surface and throughout the soil in some pedons. A few fine or medium rounded ironstone pebbles are present in some pedons. Reaction is strongly acid to extremely acid, except where limed. Mottles, associated with seasonal wetness, range from about 120 to 180 cm below the surface."
>
> The A or Ap horizon has hue of 10YR or 2.5Y, value of 4 to 7, and chroma of 1 to 4. Texture commonly is loamy sand, sandy loam, fine sandy loam, or loamy fine sand, and less commonly fine sand or sand.
>
> The E horizon has hue of 10YR or 2.5Y, value of 4 to 7, and chroma of 2 to 6. Texture commonly is loamy sand, sandy loam, fine sandy loam or loamy fine sand, and less commonly fine sand or sand.
>
> The BE horizon, where present, has hue of 10YR or 2.5Y, value of 4 to 6, and chroma of 3 to 8. Texture is sandy loam or fine sandy loam.
>
> The Bt horizon has hue of 7.5YR to 2.5Y, value of 5 through 8, and chroma of 3 to 8. Texture is mainly sandy clay loam but includes sandy loam, fine sandy loam, or clay loam. In some pedons, the Bt horizon below 100cm includes layers of sandy clay or clay textures. The lower Bt horizon is commonly mottled. Iron depletions that have chroma of 2 or less are at depths of 4 to 6 feet.
>
> The BC horizon, where present, has hue of 5YR to 2.5Y, value of 4 to 7, and chroma of 1 to 8 or it is mottled with these colors. Texture is sandy loam, fine sandy loam, sandy clay loam, clay loam, sandy clay or clay. In some pedons, this horizon contains firm, brittle, strong brown to or nodules of plinthite, but no horizon within 150cm of the surface has as much as 5 percent plinthite.
>
> The C horizon, where present, has hue of 2.5YR to 5Y, value of 4 to 8, and chroma of 1 to 8 or is mottled with these colors. Texture is commonly sandy but it ranges to clay in some pedons.

These limits define the range of the series. **According to ST**, they should all fit within limits of the series' family and all higher taxonomic levels. In addition, **all limits defined by higher levels should be respected**. For example, the Bt in the Norfolk series is allowed to have some clay or sandy clay in the lower part; this is not in the control section and so does not change the fine-loamy family particle-size class. Also, the base saturation is <35% (because this is an Ultisol), even though this is not mentioned explicitly in the range of properties.

In a 'mapping series' (as opposed to a taxonomic series) it is allowed to have ranges of properties that cross limits established at higher levels, as long as the total range of the properties is not so large as to make interpretation impossible.

The controversy over mapping vs. taxonomic series is clearest in this section of the series description.

<u>'Competing' and 'Associated' series</u>

A **competing** series is in the same family or in closely-related families, which 'competes' for the pedons that are actually classified in the named series. The differences are relatively minor, but were considered important enough to establish new series. In the past, many of these would have been grouped into a single series.

For example, from the Norfolk OSD

> “COMPETING SERIES: These are the Orangeburg series in the **same family** and the Addielou, Allen, Avilla, Bama, Bonneau, Etowah, Holston, Leesburg, Minvale, Nella, Noboco, Octavia, Pikeville, Ruston, and Smithdale series in **closely related families**. Bonneau and Addielou soils are in an **arenic subgroup**. Allen, Bama, Etowah, Nella, Orangeburg and Ruston soils have **all or some part of the Bt horizon in hue of 5YR or redder**. Avilla, Holston, Leesburg, Minvale, and Pikeville soils have **coarse fragments that exceed 10%** in all or some part of the solum. Noboco soils have **low chroma mottles associated with wetness at depths of 75 to 120cm**. Octavia soils have **more than 35 percent clay in the lower Bt horizon**.”

Note that each competing series is almost always **similar** and thus shares one or more class limits with the named series. Usually they are very similar, and are separated on a few fairly minor characteristics. In the present example, they are slightly redder color, a few coarse fragments, mottles deep in the profile, and increased clay deep in the profile. In almost all cases (and in all the cases in this example), the competing series would be allowed as **similar inclusions** in consociations of the named series. However, many of the competing series do not occur on the same landscapes as the described series.

An **associated** series is found on the same soil landscape. Some of these may be competing series, but most will not be, because of important differences in properties across the local landscape. For example, from the Norfolk OSD:

> “GEOGRAPHICALLY ASSOCIATED SOILS: In addition to the competing Bonneau, Noboco and Orangeburg series, these include Aycock, Butters, Caroline, Craven, Duplin, Exum, Faceville, Forestone, Goldsboro, Marlboro, Lakeland, Lynchburg, Rains, and Pantego series. Aycock and Exum soils have a **fine-silty particle-size class**. Butters and Foreston soils have a **coarse-loamy particle-size class**. Caroline, Craven, Faceville, and Marlboro soils have a **clayey particle-size class**. In addition, Caroline and Craven soils have **mixed mineralogy** and Faceville and Marlboro soils are **kaolinitic**. The moderately well drained Goldsboro, somewhat poorly drained Lynchburg, poorly drained Rains, and very poorly drained Pantego soils are in the same landscape as the Norfolk soils but are in **lower positions** on the landscape. Lakeland soils have **sandy textures that exceeds 2 meters**.

Some of the associated series will be similar, because they share a class limit, e.g. Goldsboro. Others are dissimilar, e.g. Lynchburg. They all can be found on the same local soilscape with the named series. In many cases (except for the competing series that are also geographically associated), the associated series would be considered **dissimilar inclusions** in consociations of the named series. But, some of the associated series, other than the competing series, might be considered similar inclusions.

4.3.4 Defining a soil series

A series should not be established without solid evidence as well as a good reason. Here we find the classic difference, found in all classification systems, between those scientists who prefer to have larger groups as long as the differences are not too great (the ‘lumpers’) and those who like to show small differences (the ‘splitters’).

The ‘lumpers’ run the risk of not showing important differences; the ‘splitters’ run the risk of (1) showing meaningless differences which just confuse the client and (2) showing apparent differences which in fact are not real, just artifacts of insufficient sampling and correlation.

<u>When is a new series justified?</u>

A new series can be considered when:

1. There are soils with **significantly different properties** from either any existing series, or other soils in the same series; *and*

2. These soils occupy a **significant area** that is **geographically coherent**, *and*

3. These soils can be **consistently separated** from other soils.

The 'lumpers' add another criterion:

4. These soils **behave differently** for one or more **important land uses** or **landscape functions** than existing series (or the other part of the existing series that is to be split).

<u>(1) Different properties</u>

This has two cases:

(1) the soils do not fit in the ranges of any established series, *or*

(2) the soils occupy only a part of the range, but are consistently different from soils in other parts of the range

Case (1) are truly new series, not derived from any existing series. They are required if a limit from ST is crossed (if the series is defined in ST). They are also required if soils are found that were previously not mapped and which can't be assigned to any existing series, because of significant differences.

> For example, in the Edgecombe County survey, large areas of mixed, thermic Typic Udipsamments were found on the Tar River terraces, as relict sand bars. The soils were morphologically similar to siliceous, thermic, Typic Udipsamments (Lakeland) with less weatherable minerals, which occur on coastal plain (not alluvial) terraces. Before ST, these soils could have classified with Lakeland, but because of their weatherable minerals, they are in a mixed-mineralogy family and thus *must* be in another series. However, even without the limits of ST, it is a good decision to make a new series, because the weatherable minerals make a significant contribution to native vegetation and pasture grasses, even in such a sandy soil. The new Tarboro series was established for these soils.

Case (2) are 'derived' series, which split an existing series into two. They occur because the correlator decides they are 'different enough' and 'extensive enough' to require a new series.

> In the example of the Tarboro series, these soils would previously have been mapped with the Buncombe soils in the same family. However, Buncombe soils have C horizons that typically have loamy textures below a depth of 1 meter and are on flood plains; Tarboro soils are not flooded and do not have loamy textures at any depth. These are important differences which affect interpretations, so that a new series is justified.

<u>(2) Significant geographical extent</u>

First, there must be **polypedons larger than the Minimum Legible Area** (MLA) of the proposed series at **typical mapping scales**, not just isolated pedons or small polypedons, e.g. isolated Udipsamment 'islands' in a map unit of fine-loamy, mixed, semiactive, thermic Typic Hapludults (State series).

Second, there must be enough **total land area** with the proposed new series, otherwise it is not worth the effort to establish the series. If this criterion is not met, the soils would be called **variants** of the existing series if they fit in the family, otherwise **taxadjuncts**.

(3) Consistently mappable

Even if polypedons larger than the Minimum Legible Area are shown to exist by field studies, the new series must be mappable by ordinary field methods.

> For example, if the areas of proposed Tarboro series occurred on the same landscapes with the established Buncombe series, it would be very hard to separate them on the basis of their main difference, i.e. the deep loamy layers of Buncombe vs. the consistently sandy profile of the Tarboro. A dense pattern of borings would be required. However, in fact the Buncombe soils usually occur on active floodplains, whereas the Tarboro soils occur on low terraces that are not flooded; this is easy to map.

Administrative procedures

A series is usually proposed by a party leader in the course of the investigative mapping, but sometimes during the routine mapping, when the geographical extent of the proposed series becomes clear.

The regional correlator then evaluates the evidence submitted by the party leader to ensure that the series meets the criteria given above.

Finally, the series is **established** and added to the master classification legend of the area.

4.4 Phases

In any soil classification system, there will be soil characteristics that are not considered at any level. Also, in any area to be mapped there will be non-soil land characteristics that are important to land use, that can be mapped with the same methods and at the same time as the purely soil characteristics. These are the two motivations for the concept of **phases** of any higher taxon.

According to Avery [1, p. 70]:

> "**Phases** are **functional groupings** used in conjunction with the formal soil … classification to **increase the usefulness** of particular soil surveys. They may be differentiated by **any soil or land attribute or combination of attributes significant to land use or behavior**. Any value of a property can be selected as a basis for division [into phases], the choice of properties and limits being determined by the objectives and by how consistently the criteria can be applied". (emphasis mine)

The USDA puts this a little differently [48. p. 21]:

> "If a property of a taxon has **too wide a range for the interpretations** needed or if some **feature outside the soil itself is significant for use** and management, these are bases for defining phases. … phases can be based on attributes such as frost hazard, character of the deeper substratum, or physiographic position that are not characteristics used to identify taxa but, nevertheless, affect use and management. If these vary from place to place within the survey area, phases can be defined to accommodate the differences."

And recall that in the definition of Soil Series, the USDA said:

> "The surface layer and such features as slope, stoniness, degree of erosion, and topographic position may vary unless these factors are associated with significant differences in the arrangement of horizons."

These features were explicitly excluded from all categorical levels by the designers of Soil Taxonomy. Therefore, if they are important to interpretations (obviously they are), they must be mapped, so we must define a new concept to map them; this is the phase.

We can identify **four kinds of phases**:

1. **Soil characteristics of the surface layer** that have been explicitly excluded from Soil Taxonomy or local classification systems (Historical note: these used to be called the 'soil type' in the USA).

   Examples: texture, coarse fragments, amount of erosion or truncation. A good example is surface stoniness: the number, size, type and pattern can have a major influence on erosion hazard, heating and drying, tillage etc.

2. **Internal soil characteristics not included in the definition of the soil Series**, because they are **deeper** than the **series control section** (in general, 150cm below the soil surface, or 200cm if in a diagnostic horizon, or 25cm into a densic or paralithic contact, or at a lithic contact), they must be taken into account in phases. These are 'substrata' phases..

3. For maps of higher categorical level than soil Series, **any internal soil characteristic not used at higher levels of Taxonomy**. Many of these could be used to define Series.

   Example: 'Typic Ustorthents, fine-loamy, mixed, mesic, subactive; **moderately deep**' for soils that are between 50 and 100cm to a root-limiting layer. The 'Lithic' subgroup is defined for soils <50cm; for deeper soils there is no difference in classification at family level. A series would be set up in detailed survey.

   Note the convention of writing the phase after a **; semicolon.**

4. **Non-soil land characteristics**. Soil surveyors map these because the surveyor sees them and infers their importance for land use or behavior. In many cases the soil surveyor is the only person who maps the relatively permanent land characteristics, so not just soil but also physiography etc.

   Example: site slope, physiographic position (e.g. terrace level to infer flood hazard).

Phases are defined on the basis of land uses (i.e., interpretations):

> "The justification for most phases rests on behavior of soils under use. At least one statement about soil behavior must be unique to each phase of a taxon, and the **differences of soil properties must exceed normal errors of observation**." [48. p. 22]

The last statement means that the **phase must be mappable**. For example, we probably should not define stoniness phases of 0-1%, 1-2%, 2-3% etc. because the variation of stoniness in the field is almost surely greater than 1% in any mappable area.

In summary, we have to meet three criteria to in order to define a phase:

1. **Important for one or more land uses** or internal soil behavior

2. Consistently **mappable**

3. **Not included** (at least at the desired level of detail) **in the definition of any higher taxa**

Historical note: In the USA, where the concept originated, phases were introduced mainly to allow more reliable interpretations of erosion hazard, for conservation farm planning. Almost all surveys include: surface texture, slope, coarse fragment and actual erosion phases.

Names of phases

The phase is named after the series name, e.g. 'Marlboro sandy loam, 2 to 6 percent slopes, eroded'. Here 'Marlboro' is the series name. If no surface texture phase is given, the map unit is named 'Marlboro soils'.

Any categorical level can be given a phase name, e.g. 'Udifluvents, frequently flooded'.

Any type of map unit can be given a phase name. The phase name can apply to the entire map unit, e.g. 'Norfolk-Goldsboro fine sandy loams, 0-3%'. Or, individual components in an association can be given phase names; these are the names that would have been given to individual components at a larger scale. Example: 'Tarboro sand, 3-8% - Portsmouth sandy clay loam, 0-3% association'.

Kinds of phases

Here are some examples of phases. Remember that others can be defined according to local conditions. See the SSM, Chapter 2, for a detailed description.

1. Texture of the surface layer, including thin depositional layers. This is almost always indicated in the map unit name.

   Historical note: the soil 'type' was a subdivision of the soil series according to surface texture. This is no longer used in the SSM. Instead, many 'types' now correspond to different series, because the surface texture differences correspond to other differences (e.g. family particle-size class) which are used to define series. Other 'types' are now phases.

2. Recent surficial deposits that were ignored in the definition of the series: overblown, hummocky, overwash

3. Rock fragments: number, amount, type and pattern. Example of amount, for size 'gravel': non-gravelly, gravelly (interferes with tillage), very gravelly (quality of tillage is affected), extremely gravelly (tillage is impossible)

4. Stoniness

5. Rockiness (outcrops): proportion, pattern, type (rippable or not)

6. Soil depth

7. Soil water behavior, e.g. surface ponding

8. Slope: degree and form

9. Salinity; sodicity; other chemical characteristics not included in the series definition

10. Physiographic position

11. Actual erosion: amount & type; degree of truncation
12. Thickness of horizons (within the boundaries of a series)
13. External climate
14. Flooding hazard
15. Degree of exploitation or alteration (e.g. organic soils, drained soils)

Some of these are clearly not soil characteristics, and instead belong in geomorphic survey (e.g. flooding hazard); for practical reasons the soil surveyor may be asked to map them, and they certainly do affect interpretations.

Some of these are unique to Soil Taxonomy, because it explicitly excludes certain internal soil properties from its diagnostic criteria, on the grounds that they are either not permanent (e.g. thin aeolian layers) or that they should not separate pedons at the series level that in the recent past were similar (e.g. truncated and severely-eroded soils).

4.5 Soil patterns within delineations

Within the delineations of the map units of an area-class maps, if there are different soils at some taxonomic level, or different phases, they occur in different spatial patterns. This may have significance to the map user, especially on two-stage maps.

This section gives some possibilities.

(1) Homogeneous

Only one soil in the delineation (within the range of the taxon); no inclusions. This is only realistic with cartographically detailed, categorically general maps, e.g. 1:10 000 map of families.

This can be divided by boundary type to the adjacent soil type: abrupt vs. transitional.

(2) Intermixed with no discernable pattern even at large scale (random)

Also called ‘regular patchy’, or more informally, ‘Swiss cheese’. The components are intricately associated. This is the commonest pattern. The size of a typical patch should be stated.

(3) Regular cyclic

Soils follow a cyclic pattern, with a characteristic dimension. Classic examples are the micro-highs and micro-lows of Vertisols. Another example is frost polygons.

(4) Regular non-cyclic

The components are regularly associated, e.g. in a hillslope catena. Give the linear scale of the association. This is the usual case in two-stage maps of soil associations.

4.6 Names of Soil Map Units

The legend of the soil map and the soil survey report must give names to each map unit. For each category, the name must show:

1. the **main soil or soils in the unit**, at the appropriate categorical level;

2. the **categorical level**

   2.1 soil series, using its local name
   2.2 higher levels of a hierarchical classification system (e.g. Soil Taxonomy, WRB)

3. **phases** at any categorical level and of any type of map unit

4. the **type of map unit**

   4.1 consociation
   4.2 undifferentiated group
   4.3 association
   4.4 complex
   4.5 unassociated soils

Some rules for naming map units; see [58] for details:

1. 'Consociation' is understood and need not be explicitly named

2. 'Undifferentiated group' and 'Unassociated soils' are not named as such, but are implied by the use of the conjunctions '*and*' and '*or*', respectively.

3. In all map unit types except the consociation, the correct conjunction must be used to separate soil names:

   3.1 consociation (none)
   3.2 undifferentiated group *and*
   3.3 association -
   3.4 complex -
   3.5 unassociated soils *or*

4. Phase designations follow the names of individual components, or they can apply to the entire map unit. The surface texture always comes first, then a comma, then other phase designations. If no surface texture is used, the word 'soils' is substituted at the series level. At higher levels, the letter '*s*' is appended to the taxonomic class.

   Phases of taxa of higher level than the family can include all or part of the family modifiers as phase modifiers. E.g. 'Udults, thermic'.

<u>Examples (Soil Taxonomy)</u>

A consociation at the level of phase of series: 'Norfolk loamy sand, 2 to 6 percent slopes, eroded'

Same, with no phase: 'Norfolk soils'

A consociation at the level of phase of family: ‘Fine-loamy, kaolinitic, thermic Typic Kandiudults, 2-6% slopes, eroded’

Same, with no phase: ‘Fine-loamy, kaolinitic, thermic Typic Kandiudults’

A consociation at a higher taxonomic level: ‘Typic Kandiudults’

Same, with a phase taken from the family name: ‘Typic Kandiudults, fine-loamy’

An association of phases of series: ‘Marlboro sandy loam, eroded – Duplin sandy loam association’

An association of phases of higher taxonomic classes: ‘Typic Udipsamments – Typic Umbraquults association, thermic’

An undifferentiated group at the phase level: ‘Norfolk, Aycock and Marlboro soils, 15-25% slopes’

An undifferentiated group at a higher taxonomic level: ‘Typic Udipsamments and Arenic Hapludults’

Examples (WRB)

A consociation at the level of phase of second-level group: ‘Chromi-Vertic Luvisols, shallow’

4.7 Estimating map unit composition

The final question in this chapter is: **How do we determine the map unit composition?** We have been happily talking about 20% inclusions, 50% of the named soil, etc. Where do these numbers come from?

In the following analysis, when ‘measure the area’ is mentioned, the easiest way to do this is by digitizing and using the GIS to measure areas.

Note that estimating map unit composition, with respect to the mapping legend, is different from estimating the composition, with respect to a soil characteristic of interest (e.g., depth, salt content,…). See [14] for a good introduction to this latter.

References: [57] gives a good introduction to the relevant statistics. From the same publication, [11] compares different methods for estimating composition.

4.7.1 Geomorphic analysis

For **associations** where the different components occupy known landscape positions, and could be mapped at larger scales, we can make a map of a sample area of the association at a larger scale (i.e., show the components separately), and then measure their relative area within the association.

> Example: in a catena we may have a soil on the shoulder hillslope position, another on the straight slope, and another on the footslope. Mapping the components at a large scale in a few sample areas, and then measuring their areas, we may find 20% shoulder, 60% straight slope, 20% footslope.

To get statistically-sound estimates, this should be done several times, and then not only the mean composition, but also the confidence intervals of the composition, can be calculated.

In practice, the surveyor often estimates the proportions of each landscape component by eye, using airphotos that show the different components. These can be quite accurate.

4.7.2 Transects

These are commonly used to estimate map unit composition, and have the advantage that they are statistically sound (unbiased) and give estimates of their error (confidence intervals). The basic methodology was worked out in the Netherlands by de Gruitjer and Marsman [22].

This method has an office, field, and another office component.

Step 1: In the office, a random sample is made of delineations within the map unit, up to some pre-determined fraction of the map unit's area. With a GIS this is simple: out of the database of all delineations, select only those from the map unit in question, and number them consecutively. Draw random numbers from 1 to the number of delineations, until the required number of hectares is sampled. To avoid a bias to small delineations, the probability sampling can be weighted by the delineation size.

Step 2: In the office, two orthogonal transects are drawn on the map, in each selected delineation. The orientation (azimuth) of the transects should not be important. A variation is to ensure that one of the axes goes 'across the grain' of expected variability within the unit.

Step 3: In the office, sample points are established at regular intervals. They should not be within the Maximum Location Accuracy distance of the boundary.

Step 4: The points are sampled in the field. Each observation is assigned to a legend category, i.e., where it best fits in the mapping legend. If it varies somewhat from the stated range of a taxon, it is listed as 'similar to' the closest taxa. If it is unlike any taxon in the legend, it is assigned to an ad-hoc 'other' category.

Problem: field location. Precise location within a map unit isn't really necessary; however it is vital to know whether one is in or outside the map unit. A digital soil survey will help here: the transect can be established on-screen and the actual grid coordinates of the sample points recorded. Then we can navigate to these points.

In practice, we may encounter 'non-soil' or 'disturbed soil' points that fall on roads, in ditches etc. Some authors recommend ignoring them, others moving to the nearest feasible sample point. It seems logical to *include* points that are 'soil' and *exclude* points (*not* relocating the sample) that are 'not-soil', e.g. roads and buildings, where the user does not expect the soils map to give any information; this would then give the composition in the 'soil' area. Independently, the proportion of 'non-soil' or 'disturbed soil' can be estimated by the proportion of points that were excluded.

Step 5: In the office, the observations are summarized with standard statistical procedures, which are summarized here, following the comparative study reported by [11].

<u>Statistical procedures for characterizing transects (1) : binomial distribution</u>

This is appropriate for a consociation with one named soil. The idea is to estimate the true proportion of the named soil and similar soils. All others are considered 'impurities' and are grouped together as 'other'. Each sampling point is considered a separate trial with two possible results: in (fits the taxa or similar) or out. In this case, the binomial distribution is used; this simple distribution characterizes the expected outcome of *n* repeated true/false trials where the true (but to us unknown) proportion of successes is *p* and of failures $q \equiv (1-p)$. The variance of *n* trials is $(p \times q) / n$.

The **estimate the true proportion** *p* is simply:

$$\hat{p} = r/n$$

where *r* is the number of successes out of *n* samples.

The **confidence interval** around *p* is estimated by:

$$\hat{p} \quad \pm \quad \left[Z_a \left(\frac{\hat{p} \cdot (1-\hat{p})}{n} \right)^{1/2} + \frac{1}{2n} \right]$$

where Z_a is the standard normal deviate for which probability of a greater value that the deviate is α, roughly speaking, the probability of this confidence interval being true. The factor (1 / 2*n*) is a finite-population correction that can be ignored for $n > 50$ or so; the factor then is < 1% proportion.

> Example: 30 samples, 25 in the named taxon or similar. Estimate *p* as 25 / 30 = $0.8\underline{3}$ = $83.\underline{3}$% purity. To compute the confidence interval at 80% probability, note that $Z_{0.9} = 1.2816$ (two-tailed, so we use the 90% level), and then compute the interval ± 0.104 = ±10.4%, so (69.6%…90.4%).
>
> Without the finite population correction, this would be ± 0.0872 = ± 8.72%, a slightly narrower range.

An appropriate statement in the soil survey report would be:

> "In map unit X, we estimated by statistical sampling that approximately 83% of the area of each delineation is occupied by soil X. With 80% confidence (see appendix), we estimate that the true proportion of soil X lies somewhere between approximately 70% and 90%".

Note that because the binomial distribution is symmetric, the width of the confidence interval is the same for 'successes' (named soils) and 'failures' (not-named soils). So if we've computed a confidence interval for 'successes', we do not have to re-calculate the interval for 'failures', just center it on $q = (1-p)$.

> Example (continued): Estimate *q* as (1-25/30) = 5/30 = $0.1\underline{6}$ = $16.\underline{6}$% **im**purity. 80% confidence interval: ±10.4% (same as for the purity), so ($6.2\underline{6}$%…$27.0\underline{6}$%).

We can turn the procedure around and determine the **number of samples** that would be needed to achieve a given confidence interval, with a given confidence level and assumed proportion correct.

<u>Statistical procedures for characterizing transects (2) : normal distribution</u>

Another way to look at this would be to estimate *p* in each transect (delineation) separately, and then use these various estimates of *p* as the samples in a continuous distribution that estimates the mean.

This has the advantage of allowing us to quantify the variation between and within delineations. If we assume that the various transects are from the same sample population (i.e., all delineations are from the same map unit), and that the various estimates of the true proportion are from an underlying normal distribution, we can use the *t*-statistic to calculate confidence intervals around the estimated mean. We could also use ANOVA to see if the delineations have different proportions.

The **estimated mean** is the mean of the separate estimates:

$$p = \frac{1}{m} \sum_{i=1}^{m} \left[\frac{r_i}{n_i} \right]$$

where r_i is the number of sample points in the specified class in transect *i*, which has a total of n_i sample points. This in general is *not* equal to the grand mean of all samples; it is only equal if all sample sizes n_i are equal.

The confidence interval is estimated with the help of the *standard error of the mean*, which is the pooled standard deviation divided by the square root of the number of transects.

The resulting confidence interval is:

$$p \quad \pm \quad t_{a,m-1} \cdot s \cdot / \sqrt{m}$$

where *t* is the appropriate *t*-statistic from the tables, with confidence level α and *m*-1 degrees of freedom (from the *m* transects).

> In the case of a very large number of samples, the normal deviate *Z* can be used instead of *t*; however, such large samples, approx. >50, are rare in practical survey.

Example: 6 transects, of (8, 12, 10, 16, 8, 10) = 64 samples, with (5, 8, 7, 10, 6, 8) = 44 in the named taxon or similar; the individual p_i = (5/8, 8/12, 7/10, 10/16, 6/8, 8/10). Estimate *p* as the mean of these fractions: (5/8, 8/12, 7/10, 10/16, 6/8, 8/10) / 6 = 0.69$\underline{4}$ = 69.$\underline{4}$% purity.

> Note that this does *not* equal the proportion estimated with all sample points taken together: 44 / 64 = 68.75%.

The standard deviation of these proportions is 0.0703 = 7.03%; the resulting standard error of the mean is 2.87%. Note that the coefficient of variance *s* / *p* is only 10.1% in this case, indicating that the various transects are very different.

To compute the confidence interval at 80% probability, note that $t_{0.9,5}$ = 1.4759 (two-tailed, so we use the 90% level), and then compute the interval ± 1.4759 × 0.0287 = ±0.0424 = 4.2%, so (65.2%…73.6%).

> Pooling this same data and using the binomial confidence intervals at the same 80% confidence level gives an interval of 68.75% ± 8.2%, so (60.5%…77%).

4.7.3 Block sampling

The Soil Survey Manual [48, p. 229] briefly mentions these.

Instead of a line (transect), identify a representative **area** and set up a **grid sampling scheme**. Analyze as for a line transect.

4.8 Soil systems

A useful way to organize our knowledge about the soils in a geographic area is the **soil system**. We will see the intimate association between this idea and the **field mapping key**. A nice example of the soil systems approach is by Daniels *et al.* from North Carolina, USA [19].

<u>Advantages of a soil systems approach</u>

1. Clear communication with non-specialists about soil-landscape relations in a restricted geographic region;

2. Logical approach to a field mapping key.

3. A small-scale map of soil systems can often be enlarged to a large-scale map, with a modest field effort, since the pattern of soils within the system is known.

4. Conversely, the soil system is a logical basis for map units of small-scale maps (i.e., associations of phases of soil series).

5. The concept of 'key soils' and then variations keeps the most important differences in mind.

<u>Definition of 'soil system'</u>

According to Daniels *et al.* [19]:

"A **soil system** is a **recurring group of soils** that occupies the landscape from the interstream divide to the stream. The soils that make up these systems usually occupy **specific landscape positions** as a result of the **internal soil environment** produced by the **interaction** of:

- stratigraphy;
- hydrology;
- geomorphology; and
- climate.

"A change in one or more of these **major controlling factors** usually results in a change in the soil system."

"Examples of major controlling factors are:

- the amount of dissection in the [Atlantic] Coastal Plain;
- bedrock type in the Piedmont;
- elevation in the [Appalachian] Mountains".

The ‘soils’ of this definition are usually (phases of) soil series, i.e. recognizably homogeneous groups of soil individuals that have a narrow range of properties, sufficiently narrow for precise interpretations.

Soil region, soil sub-region, soil system

Note that all of these can be defined only after the study of the soils in a region. The region, sub-region and system are all somewhat arbitrary concepts, and there is no attempt to standardize their definition.

The **soil region** is a large geographical area with constant values or a limited range of major controlling factors. It is usually defined by physiography, e.g. ‘Atlantic Coastal Plain’. It often corresponds with a particular pattern of land use; in fact in the USA it is quite similar to a Major Land Resource Area (MLRA) [46]. But, its limits are defined by soil-forming factors, not land use.

The **soil sub-region** is a division of the soil region with a more limited range of major controlling factors. It is also usually defined by physiography, e.g. ‘Lower Coastal Plain’.

The **soil system** is defined within a soil sub-region, as an easily-recognizable unit with specific major controlling factors. E.g., ‘Lower Coastal Plain - Pamlico System’. However, a soil system may cross sub-region or even region boundaries, if the local soil-forming factors also cross these boundaries. E.g. ‘Organic Soil System’.

Specification of a soil system

A soil system is conventionally specified by:

1. The constant values or limited range of its major controlling factors, i.e. the **context**;
2. **Block diagrams** showing the main variations in the major controlling factors within the system;
3. A group of **key soil series** which illustrate the central concepts of the soilscape; these have wide extent and are quite distinct from each other;
4. **A table of the soil series** that occur in the system, organized by the major differences in landscape position and/or internal characteristics;
5. **A relationship diagram** showing the key soils and associated soils, with arrows showing the transitions between soils. This diagram is very nearly a **field mapping key**.

5 Survey methods

In this section we investigate how a soil survey is actually made. First we discuss the main problem, which is that soils can't easily be sampled, and then three approaches to survey that, in different ways, try to solve this problem.

The fundamental problem with soil survey is that **we can directly observe only a tiny fraction of the soil**, and this sampling (by auger or shovel) is usually **destructive**, i.e., once we have sampled a site we have destroyed its original characteristics. In a few unusual circumstances we can observe some properties of the soil non-destructively and over the entire space (ground-penetrating radar, airborne imagery of the soil surface), but in general we must dig. In practice we rely on *associated* (external) characteristics that we feel are associated with soil *genesis*, i.e., why the soil is there in the first place. Foremost among these are geomorphology (landform analysis) and vegetation/land use. So, even though we have seen the soil itself in a minuscule proportion of its total volume, by relating soil properties to visible landscape features (if possible), we can reliably infer soil properties over the entire landscape.

Key concepts:

- How is the area covered? Synthetic vs. analytic approaches
- Survey methods: non-systematic, grid, continuous, physiographic, free
- Geo-pedological method for semi-detailed soil surveys

5.1 How is the area covered?

We want to map the occurrence of soils at all points in a survey area. There are two approaches: *analytic* and *synthetic*, as follows:

To understand how free survey works, we first must understand the difference between 'synthetic' and 'analytic' approaches to mapping.

5.1.1 Synthetic and analytic approaches

When we try to divide the landscape up into units, there are two fundamental approaches: synthetic and analytic.

- In the **synthetic** approach, we first make observations, and then try to **group** them so that the resulting map units separate as much of the variability as possible. The 'synthesis' is the forming of spatial units from point observations. In summary:

    1. Make a set of point observations;

    2. Group them into map units so that *inter-unit* variability is *maximized*, and *intra-unit* variability is *minimized*.

- In the **analytic** approach, we first **separate** the landscape into 'natural' soil bodies, using external characteristics such as landform, vegetation, and surface soil, and then **characterize** the resulting units by sampling. The ‘analysis’ is the separation of ‘natural’ soil bodies based on external clues. In summary

1. Divide the landscape into components such that we expect that they will have different soils;

2. Characterize the resulting units by sampling.

So, we can call the synthetic approach ‘ bottom-up’ or ‘name and then group’ approach; the analytic approach a ‘top-down’ or ‘divide and then name’ approach.

In practice, neither approach is applied in its pure form. In the synthetic approach, the placement of observations very often follows external clues which suggest where boundaries between important soil differences will occur; in fact these clues are usually the same external characteristics used in the analytic approach. In the analytic approach, the placement of boundary lines is often supported by borings; also, two ‘natural’ soil bodies as seen on the airphoto may turn out in fact to be so similar that they are grouped (as in the synthetic approach).

The problem with the pure synthetic approach is that it doesn’t take advantage of the systematic effect of soil-forming factors on the resulting soil; in its purest form it is strictly a mechanical means of obtaining maximum statistical separation between observations. For this reason, most free survey is done with analytic approaches. The synthetic approach may be applied in areas with **low predictability**, i.e. where external clues do not help separate soils.

5.2 Survey methods

We can divide surveys into the following main classes:

1. Non-systematic survey

Boundaries are determined from other maps such as geology and physiography. Widely-spaced field checks are used to determine typical soil properties. There is no estimate of internal variability. They should not be used at scales > 1:500 000, and in fact it is better if they are not real maps, but rather ‘sketches’ and not incorporated into a GIS.

2. Grid survey

A systematic sampling scheme is designed, taking into account the expected range of spatial auto-correlation. Sample points are located in the field and characterized. Standard statistical and geo-statistical methods are used to estimate variability.

3. Continuous survey

Remote sensing of the soil itself or a closely-related property (e.g. gray tone, vegetation, crop yield). Note that the resolution of the sensor dictates the survey scale, although the survey can later be generalized to a smaller scale.

> Example: Satellite sensor with 30m×30m pixels, at the Vink MLD this $900m^2\_g = 25mm^2\_m$ when linear 30m_g = 5mm_m, i.e. 1:6 000. But this is the extreme case; to avoid excessive sensor noise we should probably group four sensor pixels into one ground sample, so the maximum scale is then 1:12 000.

By a similar analysis, we see that a SPOT panchromatic sensor (10m×10m pixels) can support a continuous map at 3× this scale, i.e. 1:4 000.

For a ground-based or near-ground sensor, the map can be at any scale, but in general a pixel size is chosen that corresponds to the minimum resolution of detailed management, e.g. 'continuously'-variable fertilizer application actually has a linear resolution of about 10m.

Continuous survey provides very accurate estimates of internal variability.

4. Physiographic survey (API)

Airphoto interpretation of landforms, followed by field checking of map unit composition, sometimes only in sample areas, i.e. not all the delineations are actually visited. Sampling is biased towards 'typical' landscape positions, so only crude estimates of internal variability. The **ITC Geopedological approach** is of this type.

Typical scales: 1:50 000 to 1:200 000. At smaller scales, only landscapes and large landforms can be delimited.

5. Free survey

This is an extension of the physiographic survey. It starts with a detailed physiographic airphoto interpretation, but in this case all boundaries must be verified and possibly modified by field investigation. The surveyor actually walks most of the landscape, usually in traverses 'across the grain', concentrating on problem areas. In areas with poor correlation of geomorphology to soils (e.g., blankets of volcanic ash in Ecuador, recently-emerged polder soils), the field observations themselves are used to locate the boundaries. There are enough observations, albeit usually biased, to obtain a fairly good estimate of internal variability.

Typical scales: 1:12 500 to 1:25 000

5.3 Free survey

So called 'free' survey refers to a method of creating area-class maps where the surveyor is 'free' to choose sample points in order to systematically confirm a mental model of the soil-landscape relationships, draw boundaries, and determine map unit composition. Thus the surveyor's judgement and experience are very important. Some areas may have very few observations, if they fit exactly the mental model (i.e., the soil pattern can easily be predicted); other areas ('problem' areas) may be sampled in detail. The idea is that with the same sampling effort, a better map is made by concentrating on problem areas.

5.3.1 'Active field survey': hypothesis/confirm

The surveyor creates a **mental model** of the soil forming factors, and locates observations to confirm or modify the hypothesis. Less observations are made in areas where the hypothesis works well, and where the factors are seen to be regular. More observations are made in 'problem' areas.

Example from the Atlantic coastal plain of NC: soils of the uplands are largely the result of:

1 geomorphic surface (= exposure age), which is easily seen by well-defined scarps between surfaces,

2 granulometry of the parent sediments (from coarse sand to clay),

3 water table (drainage sequence), which is inferred from vertical and horizontal distance to drainage, and can usually be inferred from surface wetness as seen on airphotos taken in the winter (no crops, wet and cold)

Of these, (1) is very predictable, (3) is usually easily-observable on photos and only needs some field checks to confirm the boundaries between drainage classes (simple augerings to see depth to mottles and gley), so that (2) is the most problematic. Essentially, then, the field checks are aimed at determining the particle-size distribution, which correspond well to ST family particle-size classes (fine-loamy, coarse-loamy, fine-silty, clayey, sandy). The soil surveyor is mapping the sedimentary pattern. In some areas these are quite consistent and the mapping is very rapid; in other areas they are mixed and the surveyor must make many checks to determine boundaries and/or map unit composition (in the case of fine patterns of sedimentation).

Grid survey would be a waste of time in some areas: broad divides with the same drainage and same sediments; there may be delineations of 400ha that are mapped as consociations. In areas of complex sedimentation, grid survey would probably give as good or better results.

5.3.2 Mapping scale vs. publication scale

Many survey organizations use base materials for airphoto interpretation and field mapping that at a larger (more detailed) scale than the final published survey.

For example, in the Netherlands, detailed soil survey is carried out on the national 1:25 000 topographic base maps, and then generalized to a 1:50 000 publication scale [37, §29.1.3].

Reasons: more precise placement of boundaries and field observations; tentative delineations can be shown and then generalized as necessary.

Problems: generalization (see “Reducing a map to a smaller scale”, above)

5.3.3 Finding boundaries

On polygon maps, we must draw boundary lines to separate the soil continuum into more homogeneous and interpretable segments. Questions: **where** to draw the boundary, and **how** to identify this in the field or on the airphoto?

Where to draw boundaries?

Criterion: **make the most useful separation**, i.e. highest proportion of intraclass variance.

1. transition zone

2. clear separation

How to draw boundaries? Option 1: by classification of soil observations

If observations (auger holes, pits) are spaced closely enough, we can use automatic procedures to draw the 'best' boundaries, given the information we have. Or, we can estimate 'by eye'. There is a real problem with 'false precision', i.e. seeing soil bodies where they don't exist.

May be applicable in **areas of low predictability**

Option 1a: automatic boundary finding

Method: Thiessen polygons. Theoretical advantages. Use in climate maps.

Advantage: bias-free

Disadvantage: ignores other evidence

How to draw boundaries? Option 2: By landscape analysis

This is the essence of the geopedological approach. We can call this 'divide, then name'. The advantage is that the boundaries that we draw are visible over their whole length. The disadvantage is that these boundaries may not correspond with soil boundaries.

How to draw boundaries? Option 3: By other external characteristics

Sometime clues other than landscape analysis can give good correlation with soil bodies. The classic example is **vegetation**, including crop conditions. A salty area that has no obvious landscape expression is still easily visible by stunted growth of a susceptible crop, and in extreme cases by a salt crust, both visible on airphotos taken at the correct times.

Another clue is **animal activity**. For example, molehills indicate soil with at least 30cm of free drainage.

Many other examples can be given: (1) Vegetation: mangroves in tidal areas, bald cypress in seasonally-flooded river bottoms; (2) Land use: drainage canals indicate poorly-drained soils that have now been drained.

5.3.3.1 The nature of boundaries

Lagacherie et al. [39] present an interesting classification of boundaries as they occur in nature, according to two axes:

1. **Fuzziness**: How sharp is the boundary in reality?

2. **Uncertainty**: How closely can we locate the boundary from external features?

It is interesting that these occur independently of each other. There can be sharp natural boundaries that are hard to map; conversely, there are diffuse natural boundaries which are easy to map (i.e. find the center of the transition zone).

The following table, based on [Lagacherie 1996 #1139, Fig. 18.1], gives examples of landscape situations where these combinations may be found:

Examples of boundaries		**Fuziness**	
		high	***low***
Uncertainty	***high***	**Gradual** variation of the stoniness of an intermediate soil layer with **no observable surface features**	**Undetectable but abrupt** variation in the soil structure in deep soil layers
	low	**Gradual** variation of soil layer thickness, delineated by **marked changes** in vegetation / land use	**Abrupt** variation of the whole soil profile (geological change) **detectable** by a break in slope and a variation in surface stoniness

5.3.4 Areas of low predictability

A major challenge to traditional free-survey based on airphotos and soil- landscape analysis are so-called areas of low predictability, where important soil properties (typically in the subsoil) have no surface expression, neither in the vegetation or present land use, nor in their landscape position. Yet, the soils must be mapped accurately to predict the success of new uses which would rely on some of the subsoil properties.

Here are some thoughts from the USDA Soil Survey Manual Soil Survey Manual, page 230:

> "A great deal of skill and judgement is required in areas of low predictability. Rarely are the soils at two sample sites exactly alike. **Study of a single site is not enough to identify a significant area**"
>
> "Map units are defined to include the variability within areas large enough to be meaningful for the objectives of the survey. Using pre-conceived ideas of significant limits of definitive properties to define map units without regards to their geographic distribution generally results in unmappable units. Meaningless boundaries may result."

What the SSM is cautioning against is drawing meaningless boundaries between sample points. There must be enough sampling to establish that there is a real trend or separation, and that the different sample points aren't just part of one large map unit with wider variability (e.g. a complex).

5.4 Geo-pedological approach (Soil geomophology)

The 'ITC Geo-pedological Approach' to soil survey was developed by Zinck [64] and is essentially a systematic application of geomorphic analysis to soil mapping.

This approach can be used to cover large areas rapidly, especially if the relation between geomorphology and soils is close. It depends on the truth of two hypotheses:

1. **Boundaries drawn by landscape analysis separate most of the variation in the soils**; to do better would require exhaustive sampling. This will be the case if the three soil-forming factors (parent material, relief, time) which can be analyzed by this approach are dominant (not organisms, climate), and also if the mapper has correctly interpreted the photo and sample areas. The interpreter must form a **correct mental model** based on the **geomorphology** (soil-landscape relations), and apply it correctly and consistently.

2. **Sample areas are representative**; their soil pattern can be reliably extrapolated to unvisited map units

In addition, the geo-pedological approach has advantages in legend construction and structuring. It is a **hierarchical** legend system; once lines are drawn at one categorical level, they remain, even if the soils in adjacent units have the same classification. This is because of the many interpretations that are related to the 'geoforms'.

The geo-pedological approach is applied in semi-detailed studies (scales 1:35 000 to 1:100 000) as follows. The basic material are usually panchromatic airphotos with enough overlap for stereoscopic vision, at the mapping scale or slightly larger (so, 1:24 000 to 1:60 000), but other material can be used, either less detailed, such as satellite images, or more informative, such as false-colour photographs.

1. Identify the **landscapes** (level 1 of the hierarchy) on the photos (or satellite images at this level of generality) and separate these by **master lines**. There is a standard set of five landscapes with descriptive definitions: Mountain, Plateau, Piedmont, Plain, and Valley.

2. Within each landscape, identify the **relief type** (level 2 of the hierarchy) and sub-divide the level 1 (landscape) units by these. The relief types are from a fairly long list within each landscape. For example, within a Plateau landscape, we might identify dissected mesas, isolated hills, escarpments, etc. Within a Valley landscape, we might identify terraces, vales etc.

3. Within each landscape and relief type, identify the **lithology** (level 3 of the hierarchy) and sub-divide the level 2 units by lithology. Sometimes this is possible from the photo alone, but often it requires previous knowledge of the area and/or use of geologic maps. Lithology is both rock type and origin (e.g. alluvium from different fluvial systems, with different origins).

4. Within each landscape, relief type, and lithology, identify the **landforms** (level 4 of the hierarchy) and sub-divide the level 3 units by these.

5. Identify **sample areas**, which are transects (maybe with bends) 1 to 2km wide across a sequence of level 4 units, usually within one or two level 2 units. These are typically 10% of the total area, but this can be less if the overall landscape is quite uniform (i.e., repeating patterns over a large area).

6. Locate observations in each level-4 unit of the sample area in **representative locations**, i.e. where the API seems clear. Make detailed records of what soil was found. At the same time, make supplementary observations by augering nearby, of two types: (1) at random in the same physiographic position to check that the representative location really is representative (i.e., looking for possible **complexes**), and (2) as toposequence studies within an API unit, i.e. purposely looking for variability across the local landform (i.e., looking for possible **associations**).

7. If **significantly different** soils are found within a level-4 unit, decide if they can be separately mapped at the map scale by either (1) more detailed API of the physiography, or (2) API of non-physiographic elements, e.g. vegetation type. If so, expand the legend accordingly and draw new lines (level 4). The result of steps 6 & 7 is a model of the map for the whole area.

8. Now, **extrapolate** to unvisited areas, by applying the API rules developed in previous steps. Locate more field observations in order to (1) check the correctness of the extrapolation, and (2) resolve problem areas that are not clear from the API. Overall, 90%-80% of the observations are in the sample areas, and 10%-20% in the extrapolation.

Example legend from eastern North Carolina (USA):

- *1. Landscape*
  - *2. Relief Type*
    - *3. Lithology*
      - *4. Landform*

- Atlantic Coastal Plain
  - Gently-undulating uplands with well-developed drainageways
    - Pleistocene marine sediments: Middle Coastal Plain level
      - gently-undulating uplands
  - Incisions in gently-undulating uplands
    - Pleistocene marine sediments: Middle Coastal Plain level
      - Gully complex
      - Scarps
  - Flat uplands with poorly-developed drainageways
    - Pleistocene marine sediments: Lower Coastal Plain level
      - undrained flatwoods
      - margins of local drainageways
- Valleys
  - Recent river terraces
    - Tar River sedimentary complex (from Piedmont crystalline rocks)
      - point bars
      - decantation basins
      - abandoned meanders
      - …
  - Recent incised streams
    - Local creeks sedimentary complex (from Coastal Plain sediments)
      - flood plain
      - …
- Piedmont
  - …

5.4.1 The geo-pedological approach compared to other approaches

The geo-pedological legend is structured according to a fixed four-level hierarchy. This contrasts with a free-form **physiographic** approach used in many soil survey organizations, and with the **element analysis** approach to airphoto interpretation, which looks for unique combinations of API elements, without a rigid legend structure. Sometimes it may seem that the geo-pedological approach is forcing a structure that is at odds with local physiographic analysis. In particular, the position of lithology in the system as the third level is recognized by Zinck as problematic. In the previous example from North Carolina, it has been a universal practice in both geomorphic and soils mapping to separate the coastal plain levels with the second master lines (the first master line is the separation between Piedmont and Coastal Plain, which is the same as in the geo-pedological approach), yet in the geo-pedological approach, these lines do not occur until the third (lithology) level.

5.5 The field mapping key

In a limited geographic area, all we need are a few diagnostic characteristics to separate the possible soils. This makes the mapping go faster, and each observation can be rapidly classified. It is one of the tasks of the survey leader to develop a field key.

It can also be used by less-skilled personnel, e.g. extension workers who visit a farm can report on what soils they found, without having to understand the entire survey procedure.

There are three major aspects to the field mapping key: landscape position, external characteristics, and morphology.

Landscape position

This restricts certain soils to certain landscapes and positions. If the survey is already geomorphology-based, this restricts our choice of soils based on the major geomorphic divisions.

Landscape in general: e.g. different coastal plain terraces; assuming that they can be distinguished in the field, or different stream headwaters (weatherable minerals)

Landscape position: e.g., within a catena or on a specific landscape element, e.g. terrace

External characteristics

First, anything that controls soil genesis consistently in this area, and that can be easily seen in the field or on the airphoto.

Examples: Natural vegetation type; lithology

Second, anything that is consistently correlated with soil type in the area.

Example: land use. E.g. if an area is used for rice paddy, it must be fine-textured enough to puddle.

Morphology

Profile morphology, e.g. depth to argillic, mottles; texture profile. This should give the final identification of the soil. The idea is to use easily-identified characteristics, preferably visible just be augering, and to the minimum depth possible.

Some people use Soil Taxonomy as a field key. This often works, because many of the differentiating characteristics in ST are observable in the field, and represent important differences. Actually, what they do is **simplify** ST according to local conditions, leaving only the locally-relevant differentiating characteristics and taxa. Example: looking for mollic epipedons in a humid climate, you can ignore all the statements about finely-divided limestone masking the dark colors.

Problem: no one can actually determine all the properties necessary for classification in ST in the field. In practice, some characteristics used in ST are used to make a field key, which is then a gross simplification of KST.

The field key can be written as a dichotomous (two-way) key, a multi-way decision tree, or as a diagram from ‘key soils’ to variants. It may include external properties such as landscape position and geomorphic surface.

Example of a decision tree used as a field mapping key:

- Middle Coastal Plain terraces
    - Fine-loamy families of Ultisols
        - Well-drained: Norfolk
        - Moderately well-drained: Goldsboro
        - …
        - Poorly-drained: Rains
        - Very poorly drained (cumulic epipedon): Pantego
    - Fine-silty families of Ultisols
        - Well-drained: Aycock
        - Moderately well-drained: Exum
        - …
- Tar River terraces
    - Fine-loamy families of Ultisols
        - Well-drained: State
        - Moderately well-drained: Altavista
        - …
    - Psamments
        - excessively well-drained
            - >95% sand: Assateague
            - other: Tarboro
        - moderately well-drained: Pactolus
- Tar River current floodplain…

Of course, the same result could be obtained with a key written in a different way, or with a relationship diagram from key soils.

6 The soil survey map & report

This is the document that is intended to be used by the public. Therefore it should be written with the intended audience clearly in mind. Often the same information is repeated, once in more technical language to communicate with other soils specialists, and once in common language to communicate with non-specialists who use soils.

6.1 Mapping legends

Each of the more-or-less homogeneous areas of the map must be given a *name* and its properties *described*.

Mapping legend The set of map unit names is the *mapping legend*. This provides names by which we can refer to areas on the map. E.g., “This polygon represents an association of Cazenovia silt loam, 0-3% slope, and Palmyra gravely loam, 3-8% slope.” We have discussed map unit names in detail above.

Descriptive legend: the set of descriptions of their properties is the *descriptive legend*. This is the link between the map and statements that we can make about the map units. E.g., “In this polygon, the water table is always deeper than two meters.” Often this is presented in narrative form for each legend category. It can also be presented as a set of tables.

Interpretative legend: a statement about the map unit for a specific purpose, i.e., a result of land evaluation. E.g., “This area is highly suited to intensive mechanized irrigated grain crop production”. This is usually presented in interpretive tables, one table for each interpretation, with each table having an entry for each mapping unit.

6.1.1 Grouping map units in a legend

The map legend often groups ‘related’ map units. This is only necessary to communicate some higher-level or more abstract concept to the map user.

<u>Option: No grouping</u>

This is typical of USA detailed soil survey. The map units are listed in alphabetic order. Because of the naming system (i.e., phases of series), all the map units for a series are grouped together. But there is no attempt to make a higher-level grouping.

<u>Option: By landscape</u>

E.g., mountains, hills, terraces, plains… This is typical of maps made with the **geopedological approach**. It is very good to give the user an overview of the physiographic regions; these can have implications for land use.

<u>Option: By a classification scheme</u>

Not very useful to almost all users, if the classification scheme is pedologic. However, if the scheme is local and based on major properties, this is similar to the following.

The Netherlands groups map units by the Dutch classification, which is based on major profile characteristics.

Option: By major properties

The legend is grouped according to a major property of importance in the survey area, for example, drainage conditions or major parent material. This leads to legends with groups such as ‘peat soils’, ‘wet soils’, ‘upland soils’, ‘seasonally-wet soils’. This can be quite effective if the major property is of overwhelming importance for land use.

Option: By suitability or capability

The legend is grouped according to land capability (USDA), land capacity (USBR), or land suitability (FAO) for a dominant land use. This is appropriate if the survey is being made primarily to support conservation farm planning (land capability) or irrigation planning (USBR, FAO Irrigated lands). For multi-purpose surveys it is not so successful, because different LUTs will in general have different rankings of the map units.

6.1.2 Description of map unit composition

The name of the map unit (type and constituents) provides a shorthand to describe the map unit. However, both the non-technical land user and the scientist in other fields need more detailed descriptive information.

Brown & Huddleston [10] discuss how best to communicate map unit composition to the user, and show examples of good and poor communication. My suggestion, building on their work and others, is as follows:

1. Include in the report a **glossary** with a **definition of the map unit types** used in the report, such as ‘consociation’, ‘association’ etc. For example:

   > “**Consociation**: Only one soil type is named. This named soil type and closely-related soils that differ in only a few unimportant properties that do not significantly affect interpretations make up <u>at least 75%</u> of the area of a consociation. Therefore, up to 25% of the total area may contain soils that differ significantly from the named soil in one or more properties. Up to 15% of the total area may contain soils that differ significantly from the named soil, and that in addition are significantly more limiting for one or more land uses.”

   > “**Association**: Several important soil types that occur in the map unit are named. These soils occur in a regular pattern in the landscape that can be seen in the field and on aerial photographs, but can not be mapped at this survey’s map scale. The named soil types and closely-related soils that differ in only a few unimportant properties that do not significantly affect interpretations make up <u>at least 75%</u> of the area of the association. Therefore, up to 25% of the total area may contain soils that differ significantly from all of the named soil in one or more properties. Up to 15% of the total area may contain soils that differ significantly from all of the named soils, and that in addition are significantly more limiting for one or more land uses.”

   > “**Complex**: Similar to an association (q.v.), except that the named soils do *not* occur in a regular pattern in the landscape that can be seen in the field and on aerial photographs at normal map scales. Instead, they occur together in a very intricate pattern that can be discovered only by detailed on-site inspection.”

2. For each map unit, **list the inclusions**, whether they are similar or not, their estimated percentages, and if possible their landscape positions. For example, here is a hypothetical description of map unit 'Norfolk sandy loam, 0-2% slopes':

> "…Included with the named soil in mapping are a few areas of similar Goldsboro and Wagram soils, and dissimilar Lynchburg and Rains soils, as well as pedons similar to Norfolk that do not meet the exact criteria of the Norfolk series ('taxadjuncts'). Goldsboro soils have a somewhat higher water table, and Lynchburg and Rains soils have a much higher water table. Wagram soils have a thicker loamy sand surface layer. Goldsboro soils are the most common inclusion, making up 5 to 10% of most delineations and occasionally as much as 15%. They occur on slightly lower landscape positions. Lynchburg soils occur in about half of the delineations and make up 2 to 5% of these. They occur in small depressions and limit field operations. Rains and Wagram soils are rare and when present make up less than 5% of a delineation. Rains soils occur as isolated low spots too small to map. They are generally avoided during field operations. Wagram soils occur in isolated patches throughout some delineations; they present no problems for field operations but are more susceptible to drought. The Norfolk taxadjuncts occupy up to 30% of many delineations; they differ from the series definition in minor characteristics that do not appreciably affect soil management."

3. If there is transect or other field statistical data, report its results.

> "Norfolk and similar soils make up 65% to 82% of the mapped areas. Similar soils included in mapping may have a surface sandy loam layer 40 to 60cm thick, or a loamy sand, fine sandy loam, or loam texture… The dissimilar and limiting Lynchburg and Rains soils make up 2 to 12% of the mapped area… All statements are made with 80% confidence (see Appendix)."

The concept of **confidence level** is difficult for people not trained in statistics to grasp, so perhaps it should be left to an appendix. Suggested language:

> "The statistical data on map unit composition in this report are based on the **80% confidence level**. This means that, if the sample we actually studied was chosen truly at random out of all the possible samples that we could have chosen, that the composition we report has an 80% probability of actually containing the true composition. Another way to say the same thing is that if we had been able to take a large number of similar samples, 80% of the confidence intervals that we calculated from these would have contained the true composition. Obviously, we do not know if our one sample is one of those 80% or one of the 20% that does not contain the true composition.
>
> "We can always increase the confidence level by widening the confidence interval; in this way we are *more confident* of a *less precise* statement. We have attempted to strike a balance in this report between confidence and precision."

6.2 Procedures

If survey procedures are described in a standard reference, it may be sufficient just to give a reference to that (for example, the Soil Survey Manual or the ITC Geo-pedological method). However, it is better to describe how the survey was actually made. This way the user can have some idea of its quality.

If more than one method was used, often there is a small **index map of procedures**. This is an adjunct to the main map that shows how the survey area was examined. It may include, for each area: (1) which soil surveyor (see for example [26] p. 242); (2) which date?; (3) which scale of mapping, or what density of inspections; (4) what source materials were used? (e.g.: air-photo vs. satellite vs. radar).

6.3 The map

This of course is the main product of the soil survey. In this section I make some remarks over map presentation techniques.

6.3.1 Colors

A good introduction to color theory and application in cartography, including GIS, is an ITC publication by Brown and Feringa [9].

In the USA, since the 1960's, no use has been made of color. The map is just an information carrier: space is divided by boundary lines and labeled by symbols. Advantage: no visual bias, the user makes no unwarranted inferences.

Color is very attractive, but if it is used, it **must mean something**! It should reflect the legend grouping (see above). Traditional colors such as purple for peat, blue for poorly-drained mineral soils, green for well-drained mineral soils, and yellow for excessively-drained soils seem psychologically satisfying, but their use should be verified with clients. A standard cartography text such as that of Robinson *et al.* [45, Chapter 21] should be consulted for both psychological/symbol and practical issues of color use.

If the soils are grouped in a **hierarchical legend**, e.g. with the geopedological approach, the highest categorical level (e.g., the landscape level) should be assigned a major color, which are divided into variations of the basic color at lower categorical levels. Thus the map user can easily see the pattern of the major landscapes. This gives a very attractive overview of the survey area.

The worst possible use of color is if extremely different colors are used for similar soils.

Cartographic rules of thumb: more than six to ten major hues are confusing; dark colors obscure topographic reference features.

6.3.2 Spot symbols

In many cases it is very important to show 'point' conditions. By 'point' we really mean 'areas' that can't be shown at the scale of the map.

'Point' defined as < MLD; spot goes in center; spot could be almost to the size of the MLD

These points must be correctly located! They are usually quite visible on the air-photo; there may be problems transferring to a geo-referenced base with sufficient accuracy.

6.3.3 Boundaries

It would seem feasible to indicate the different types of transitions between delineations with different line symbols. For example, the line thickness could indicate the width of the transition. Or a broken line could be used for uncertain or inferred boundaries (as is done on geological maps). To my knowledge no survey organization does this. It would require the surveyor to be explicit about the transition.

6.3.4 Geometrically-correct boundaries

Problem: stereopairs of air-photo are not geometrically correct, so neither are photo-interpretation or field lines drawn on them. For a correct map, especially one that will be included in a GIS, the boundaries must be geometrically accurate and geo-referenced.

Solution 1: manual transfer to orthophotos

Solution 1 is to **manually transfer** lines to an **orthophoto** which covers the same area as the unrectified photos used for mapping. The orthophoto is a geometrically-correct base map which also shows the detail from air photos. No special device is needed; with the subtle details of the photos the lines can be re-drawn extremely accurately.

The problem is obtaining the orthophoto. To make an ortho-corrected image, see Solution 3.

Solution 2: manual transfer to a correct base

Solution 2 (traditional): **manually transfer** lines to a geometrically-correct base map (typically, a topographic map) with a mirrored light table or a zoom transfer scope. Continuously adjust by eye, work on small pieces only between adjustments. Accuracy can be high if there are dense features for interpolation. Accuracy is very high if a feature shown on the base map is followed exactly, e.g. a river or a sharp contour line. The zoom transfer scope is more precise, the mirrored light table does not require stereo vision. In both cases, the tilt and scale displacements can be removed. Radial displacement can not, hence the need to work in pieces.

Problem 1: Base map may not show enough features. E.g. large arid plain, with low relief (no contour lines), no permanent drainage ways, very sparse infrastructure, but important soil differences that are clear on the photo (salt spots, blowouts, different playas & fans).

Problem 2: Base map may be poor-quality: old cultural features, shifted natural features e.g. rivers, incorrectly-drawn contours (poor quality control)

Solution 3: rectify & georeference photo overlay

Solution 3: rectify & georeference photos. Geo-reference with 10 to 20 identifiable, sharp points that can be seen on the photo & on the base map. Typically, the mylar overlay with the soil lines is geo-referenced on a digitizer, first marking the points themselves on this same overlay.

If the software can perform **ortho-correction**, then the base map must be first converted into a Digital Elevation Model, so that each control point has an associated elevation, and the terrain form is known. This can give very good results.

Examples of control points: road intersections, building corners. For ortho-correction, points should include the highest and lowest points of the landscape.

Caution! Buildings are sometimes schematic, not geometrically correct (although their center should be correct)

Caution! Natural features may shift (especially river junctions, sand bars, land points in lakes). If possible, choose rock-controlled features, as they will not move so fast.

Problem: The so-called ‘correct’ base map may be incorrect!

Solution 4: pre-mapping with geometrically-correct maps

Basic idea: find some soil or landscape boundary lines on geometrically-correct maps, then join other lines to these.

Source 1: topographic base map: rivers, sharp contours

Source 2: satellite images. Advantage: very little relief distortion; system errors are understood and can be controlled by standard procedures. Usually can geo-reference and resample to within one to three pixel error (30 - 90m). This may be good enough for maps at 1:100 000 or smaller scales (here, MLA = 25m).

6.4 Representative sites

These are pedons from important soils of the area that have been described and sampled in detail. They provide a **benchmark** for the more sophisticated soil survey client. ‘Everything’ about the pedon is described.

- site information
- descriptive data: profile & horizons
- analytical data: physical, chemical, mineralogical, engineering tests

6.5 Communicating soil patterns to the survey user

The soil pattern both within and between delineations can be shown to the user, so that these relations will be recognized in the field.

- Block diagrams: three-dimensional drawings of the relation between the substratum, landscape position, and soils.
- Pattern descriptions. Big differences in management: e.g. isolated wet spots (easy to work around) vs. same proportion of wet soils but arranged as transverse drainage ways.
- Geo-statistics (spatial dependence) for special studies

6.6 Correlation to a soil classification system

Purpose: Makes it possible to consider technology transfer from analogous areas.

If the legend is already in a classification system, this is only necessary to correlate to another system. If the legend is of soil Series, this is necessary to relate the Series to outside experiences.

Correlation can be to a national or (several) international systems (ST, WRB…).

6.7 Soil Survey Interpretations

The soil survey itself is only interesting to the pedologist. The soil survey *consumer* is interested in *interpretations*, i.e. what the survey says about actual and potential land uses and land management strategies. If we consider soil as part of the land resource, the soil survey thus becomes an input to *land evaluation*; however we can consider just the soil resource by itself and still produce useful results. Traditionally, the phrase **soil survey interpretations** has been used to describe this process.

The basic idea is to take the map units of a detailed soil survey (e.g., US county level, map at 1:20 000, map units are usually phases of soil series) and *interpret* them directly for anticipated land uses, showing the effect of the *soil* & *related land characteristics* (named in the phase) on those uses. The result is a *suitability* for the use based on the severity of *relatively-permanent limitations*. It is *not* an economic evaluation, although the relative difficulty of overcoming the limitations is implicitly taken into account. Most often, this approach is taken for *non-agricultural* uses, such as engineering uses, whose limitations and 'productivity' can't easily be quantified in the context of a soil survey.

The emphasis is on **relatively permanent limitations** to land use, caused by the soil or associated land characteristics (typically named in the phase), e.g. slope & stoniness

The rating depends on how severe these are; this is at least implicitly an economic evaluation

The **reason** for each classification is given, i.e. the nature of the limitation.

Olson [44] wrote a textbook that uses this approach; he also produced a more detailed example for engineering applications such as suburban construction [43]. Any post-1970 soil survey from the USA has interpretive tables that follow this approach. The National Soils Handbook [51] §603.03 explains the approach, and has sample tables.

Example: (extracted from [51] Table 620-17)

Classification for septic tank absorption fields

	Limits			
Property	**Slight**	**Moderate**	**Severe**	**Restrictive Feature**
Flooding	None	Rare	Common	*Flooding*
Depth to Bedrock (cm)	>180	100-180	<100	*Depth to rock*
Depth to cemented pan (cm)	>180	100-180	<100	*Cemented pan*
Surface ponding			yes	*Ponding*
Depth to high water table (m)	>1.8	1.2-1.8	<1.2	*Wetness*
Permeability of 60-150cm depth (cm/hr)	5-15	1.5-5	<1.5	*Percolates slowly*
Permeability of 60-100cm depth (cm/hr)			>15	*Poor filter*
Slope (%)	<8	8-15	>15	*Slope*
Fraction >7.5cm (weight %)	<25	25-50	>50	*Large stones*

The ‘properties’ (leftmost column) are land characteristics that are known for each soil unit to be rated. The table is a maximum-limitation table: the rightmost column of ‘slight’, ‘moderate’ and ‘severe’ that applies gives the rating. Each map unit gets the rating *and* a list of the restrictive features.

Advantages: directly applicable to planning; if a decision procedure was developed, it provides insight into the land use. The type of limitation is made explicit.

Disadvantages: most reports don’t indicate how the map units were rated (i.e., the report itself doesn’t include the rating table). ALES decision trees could be created to do the interpretation, but sometimes the criteria are more ‘holistic’ (may give an good classification, but can’t be reproduced).

Remember, it is not an economic interpretation; the cost to overcome a limitation is only implicit. Some limitations may feasibly be removed, others not, within the context of a LUT. In the above example, it is difficult and expensive to blast away bedrock, but the depth to water table may be controlled by drainage in certain sites. Engineering feasibility is not considered in the ratings, this would have to be determined for each site.

Relation to FAO-style land evaluation: the land uses (individual tables) can be considered to be Land Utilization Types. The limitation types can be considered to be Land Use Requirements. The diagnostic soil variables can be considered to be diagnostic Land Characteristics.

7 Quality control in soil survey

In this section we present concepts and techniques for assuring and assessing the quality of a published soil survey. The surveyor can use some of these techniques to produce a better survey; the survey user can use other techniques to assess the quality of the survey that is delivered by the surveyor. There are two major activities: **correlation** in its several meanings, and **quality control** *per se*.

7.1 Correlation

Correlation means 'to relate similar things'. The term 'correlation' was originally used in geology, where it means 'to demonstrate equivalence between spatially-separated rock outcrops'; this equivalence can be lithology, age, or fossil assemblages. By analogy, 'soil correlation' means 'to demonstrate equivalence between spatially-separated soil individuals or bodies'. We use the correlation process to make sure **similar soil individuals and map areas are given the same name**. This is in several contexts:

1. Understanding the same thing by the same descriptive terms, i.e. **consistent terminology**
2. Placing field observations in the correct taxonomic category (**classification of soil individuals**)
3. Establishing **new taxa** if necessary (e.g., new soil series)
4. Establishing a **mapping legend**
5. Placing delineations in the correct legend category

In all cases, correlation is partly **scientific** (using published materials such as keys, and using field sampling), and partly institutional, i.e. based on **institutional experience**. This is similar to decisions by law courts in countries where legal precedent is important (e.g., English common law); over the years each generation of judges (= soil surveyors) aims at a **consistent** use of language.

Correlation is in practice a difficult and controversial process. It requires substantial field experience and 'institutional memory'.

7.1.1 Consistent terminology

This is not really 'correlation' *per se*, but vital for any scientific observation. All surveyors must agree on the definition and use of all descriptive terms used in the soil survey. Without this, further correlation steps are not valid, since they depend on classification of individuals and areas using consistent terminology.

Examples (point observations): field texture, consistence, structure type & grade, plasticity, 'coated' vs. 'uncoated' sands, number and pattern of mottles… (thousands of terms!)

Examples (area observations): surface coverage by coarse fragments (type and amount); slope form; degree of actual erosion…

Without this, the following steps are useless. We assure consistent terminology by good training of field soil scientists and constant checks by senior staff.

7.1.2 Classification of soil individuals

Each field observation must be assigned to a **taxonomic category**, i.e. must be **classified**. This can be an established system such as Soil Taxonomy, or a local system of Series, or even a local mapping legend. **All well-trained observers should agree on the placement of each observation.**

If there is a classification key for the system, this step should not be difficult. But in practice:

1. **Not all observers agree on whether a property meets limits of the key**.

   For example, the Dutch classification system speaks of ‘obvious Podzol morphology’; this is clear enough for ‘classic’ Podzols, but as these grade into individuals with less well-expressed morphology, where do we draw the line between ‘obvious’ and ‘not obvious’.

   Even with so-called ‘quantitative’ limits, there may be difficulties, e.g. a color right on the borderline between two hues.

2. **The key is ambiguous**

   Even in Soil Taxonomy there is a lot of room for interpretation. A good example is the definition of the argillic horizon. If the field scientist thinks that the pedon has been truncated, there is no need for an overlying eluvial horizon and a specific clay increase. The decision about whether the soil is truncated is based on field evidence, not only of the point but of the catena (e.g., Is there evidence of recent sediment accumulation in the footslope?) or of the whole area (e.g. Can we find untruncated profiles in nearby forested areas in analogous landscape positions?) or even of historical record.

3. Even though the key is clear, **the observation does not fit the concept** of the taxon.

   Soil Taxonomy allows classification of any soil; however blind application of the key may lead us to group an observation with soils that are obviously very different in properties, geography, management etc. In this case, the key is at fault; we don’t change the key or add classes without good evidence, but it can happen.

   Thus part of correlation of field observations is to determine when observations can’t really be correlated to existing concepts.

4. The key is not **complete**

   In some cases, the key is not complete on purpose. Not all combinations of properties are expected in nature, so there may be ‘holes’ in the classification system (and rightly so!).

   In a Series key, much of the character space within a Family is not occupied by a known Series. Recall that a Series must occupy a significant land area. Individual pedons may not fit the Series definition in all respects.

   Note that Soil Taxonomy is complete to the Family level; i.e., all soil individuals can be classified to Family level, thus this problem does not present itself until the Series level in ST.

In some surveys there may be no true key, but rather **central concepts** and **ranges**. This is often the case with soil series. Even in the USA, the series limits must be in the family limits, but the limits between competing series are not so firm.

7.1.3 Establishing new taxonomic categories

When the correlator feels that there are significant areas of soils that do not fit well in the existing classification system, new taxonomic categories are proposed. The correlation process uses field observations to decide on the limits of the new taxa, and their relation to existing taxa.

Most common in detailed mapping is the establishment of new soil series, because of consistent differences with existing series. Here it is vital to consult experienced soil surveyors from similar areas, to see if in fact the proposed new series is in fact a new concept. A series can be established locally without appeal to a higher authority (e.g., USDA). **However**, it may be that a suitable series has been established elsewhere. Example: many soil series first described in Cuba in the 1920's occur also in Hispaniola and Puerto Rico.

In some areas of the world whose soils have been little studied, we may even think of new categories in a hierarchical classification scheme such as Soil Taxonomy. For example, the 8^{th} revision of ST has a new Gelisols order, for permanently-frozen soils; previously these were classified as cryic subgroups of other orders, or not classified at all.

In other areas, the soils become better understood, and a new hierarchy seems better able to group similar soils. An example is the major revision of the Aridisols in the 6^{th} revision of ST. Previously, Aridisols were grouped first on whether they had an argillic horizon or not (Argids and Orthids); after studying these soils more closely, a committee decided that the major salt is a better way to group Aridisols at the top level (e.g., Salids, Calcids, Gypsids,…), and that the presence of an argillic horizon is only considered if there is no dominant salt.

The revision of a taxonomy is not a trivial decision. Many existing databases are affected. They are either revised to the new standards, or 'time-stamped' with the date of their creation, so that the names have their meanings as of that date, not their meanings as of later revisions.

7.1.4 Establishing a mapping legend

In a survey area, many more taxa are present than are mapped. We can only map soils with sufficient extent and spatial coherence, not isolated profiles. So one of the main tasks of the correlator is to establish a set of classes into which all delineations will be assigned. This is the **mapping legend** for the survey area.

Example: Edgecombe County, NC, USA. Spots of Orangeburg soils (bright red argillic horizons, 5YR) occur within large, contiguous areas of the similar Norfolk soils (yellowish-red argillic horizons, 7.5YR to 2.5Y). It is a correlation decision that the Orangeburg series, although present, is not mappable. The further correlation decision is to include Orangeburg pedons with Norfolk pedons as similar soils, for the purpose of establishing map units. Note that in other survey areas, Orangeburg soils occur widely and are easily mappable, in which case they *are* used in the mapping legend.

How is the mapping legend established?

Option 1: from detailed mapping of sample areas

If the area is fairly well-understood, and the possible taxa also, an experienced surveyor maps 'representative' sample areas in detail, perhaps at 4x the publication scale (i.e., for a 1:50 000 map, at 1:12 500), so that the area scale is 16x. This level of detail allows the confirmation of a detailed mental model.

Option 2: from observations during routine survey

Boundaries are drawn from external characteristic and point observations are recorded. After a certain amount of mapping, it should become clear which is the central concept of the mapping unit, what is the natural range of characteristics, and what are common inclusions.

7.1.5 Placing delineations in the correct legend category

This aspect of correlation is the consistent assignment of real delineations to mapping units (legend categories). In almost all cases, real landscape units will not be taxonomically pure. The 'best' assignment is the one that misleads the map user the least!

7.2 Boundary, content, and point accuracy

We can distinguish various concepts of 'accuracy', all relevant to specific statements about the mapped soil or land.

Boundary accuracy

Are the boundaries correctly placed? Is the geometry of the boundary junctions logical?

Content accuracy

Is the content of each map unit correctly described, in the aggregate? How accurate are statements about the percentage composition of the map unit? This is covered under 'Estimating Map Unit Composition', above.

Point accuracy

How accurate are statements about individual points?

7.3 Types of variables

Before talking about the 'success' of a soil survey, we need to understand the kind of information that is collected by soil survey. First, a classification of the soil-related Land Characteristics, and how they can be characterized statistically. This is covered by many authors, always using slightly different terminology, e.g. [7, Table 1 on p. 11, 21]. This are very important distinctions, because certain operations and statistics are only meaningful for certain classes of variables.

Nominal: values are from a set of *unordered classes*. (e.g., structure type of a given horizon: { massive, single-grain, angular blocky, prismatic…}). We can determine *equality* only, not rank. The only statistical measure that makes sense is the *mode* (most frequent value). There is no true estimate of dispersion. Note that the classes may be numbered for convenience, but these numbers can not be used for calculation.

Ordinal: values are from a set of *ordered classes*. The classes are usually numbered, e.g. {1, 2, … n} which shows the rank, but there are no true units of measurement, just class numbers in rank order. (e.g., structure grade of a given horizon: {none, very weak, weak, … very strong}). We can determine *equality* as well as *rank* (greater, less than). The mode is again useful, but also now the median (as a class number). We can also measure the *range*, i.e. how many classes.

Interval: values are measured on a *continuous* scale, and the units of measurement are meaningful, however there is *no natural origin* of the scale, i.e. the zero is arbitrary and does not represent a real 'nothing' (e.g., Temperature in °C). Thus, the *ratio* of two values is *not* meaningful. We can *not* say 'today is twice as warm as yesterday, since today it is 20°C and yesterday it was 10°C'; that statement is mathematically correct but only because of the arbitrary nature of the Centigrade scale. We can see this by converting to Fahrenheit: 68°F is *not* twice 50°F! The mode is not so useful, since the values are continuous; the *median* is meaningful, and now also the *mean*. To measure dispersion we can use still the range, but now also the *variance & standard deviation*.

Ratio: values are measured on a *continuous* scale, and the units of measurement are meaningful, and there is a *natural origin* of the scale, i.e. the *zero is not arbitrary*, but set from first principles (e.g., Temperature in °K, % fine sand, crop yield). Here 'zero' really means 'nothing' or 'starting point'. Thus, the *ratio* of two values is meaningful. We can say 'this soils has twice the average yield as that soil'. The mode is not so useful, since the values are continuous; the *median* is meaningful, as well as the *mean*. To measure dispersion we can still use the *range*, also the *variance* & *standard deviation*, and since there is a true zero, the *coefficient of variation* is meaningful. (Recall: CV = SD / Mean; this is a ratio).

Classified interval or ratio: values are from a set of ordered classes, defined by *class limits* of the underlying interval or ratio scale. (e.g. temperature classes). These are treated as ordinal LCs. If the class widths are equal (e.g., (0…10), (10…20), …) they can be treated as interval LCs with integer resolution; if in addition the underlying scale is ratio, the classes can be treated as ratio LCs with integer resolution

7.4 How successful was the soil survey?

If we view the soil survey as a tool for landscape stratification and prediction, we can ask, in quantitative terms, "how successful was the survey in meeting its objectives?" This is *not* the same as asking "is this the best possible soil survey?" or "how accurate was the soil survey?". Here we judge the soil survey directly.

The mapper's criterion: How well are the soils separated by the map?

The mapper may judge his or her own effort by **how well the different soils were separated**, i.e. whether the stratification proposed by the mapper is successful. There are two ways to look at mapping success:

- Classification purity
- Stratification efficiency

In the first case, the mapper wants to know if similar soils were grouped together, according to a classification system. But this may give false emphasis to classification, which may not necessarily use important interpretive properties. So, in the second case, the mapper wants to know how well soil *properties* were separated by the map.

Here the emphasis is on the mapper: did s/he do the best job possible of separating the **multivariate character space**? Here we think of the soil as a collection of measurable **land characteristics** as explained above.

We will consider three quantitative approaches:

- Single-characteristic, two delineations
- Single-characteristic, over an entire map
- Multi-characteristic

7.4.1 Single characteristic, two delineations

To illustrate how quantitative methods can be used to judge the effectiveness of soil survey, we begin with the simplest possible example: the map is divided into two parts by a single boundary line.

Consider a hypothetical area with two strongly-contrasting soils: (1) light-textured levee, (2) heavy-textured decantation basin. Suppose these soils occur in elongated natural soil bodies, aligned parallel to the axis of a river, and that each body occupied 50% of the total area. We will evaluate the effect of mapping this area in two ways:

1. with two 'correct' delineations, following the natural soil bodies;
2. with two 'incorrect' delineations, crossing the natural soil bodies

Situation 1: 'Correct' delineation

Suppose that we take 20 unbiased samples in this landscape, 10 in each of the natural soil bodies, and that the data for clay content (%) are as follows:

(correct) Map unit 1: (4, 6, 6, 8, 8, 8, 8, 10, 10, 12); n = 10

(correct) Map unit 2: (56, 58, 58, 60, 60, 60, 60, 62, 62, 64); n = 10

These numbers are 'cooked' so that correct MU2 is always 52% clay more than correct MU1.

We have two applications of the soil survey (sample points and map):

1. We want to *predict*, for any location, its clay content. We do this by (1) determining in which map unit the point lies, (2) using the sample statistics from that map unit to predict its value. So every point in the map unit will receive the same estimate (this isn't a geo-statistical estimate), based on the map and sample. The question is, what is the range of possible values of that sample?
2. In addition, we want to estimate the *mean* clay content of each map unit.

The analysis here follows Webster & Oliver [61], Chapter 3, 'Sampling & Estimation'. It is a simple use of descriptive statistics and estimate of confidence intervals that can be found in almost every elementary statistics text.

First, let's examine these with a stem-&-leaf plot [35, Ch. 1], with a step size of 1:

Map Unit 1	**Map Unit 2**
0 | 4	
0 | 6 6	
0 | 8 8 8 8	
1 | 0 0	
1 | 2	…
…	…
…	5 | 6
	5 | 8 8
	6 | 0 0 0 0
	6 | 2 2
	6 | 4

This type of plot is a sort of numerical histogram. We can see by inspection that these are symmetrically distributed, with a clear **modal** value (8 & 60, respectively) in the middle of the distribution. The mode is also the **median**. The two distributions **do not overlap**, suggesting that they are from two different populations. The distributions are **unimodal** (one peak), at the mode. They have the same variance. They are certainly 'normal enough' to compute mean and variance, which are roughly:

(Notation: x : sample mean; s^2 = sample variance, s = sample standard deviation; s_x = standard error of the mean; n = number of samples; CV = coefficient of variation).

Map unit 1: $x = 8$, $s^2 = 5.33$, $s = \sqrt{5.33} = 2.31$; $s_x = s / \sqrt{10} = 0.73$; CV = $s / x \times 100 = 29\%$

The CV is somewhat high because the mean is so low. With only 8% clay mean, even a low variance leads to a somewhat high *relative* variation, which is what the CV measures.

Confidence limits on the value: $x \pm t \times s$ for (n–1) = 9 degrees of freedom. Referring to the *t*-tables, for 80% confidence we find $t = 1.383$, so the confidence limits for Map Unit 1 are:

$8 \pm (1.383 \times 2.31) = (4.8 \ldots 11.2)\%$

This is a narrow range. It means that, **based on our sample, it is 80% probable that a random sample from Map Unit 1 will lie in the range (4.8%…11.2%) clay**.

Question: is this a narrow-enough range for interpretations? Probably not, in many cases: the influence on water & nutrient retention, stickiness & plasticity etc. is significant when we go from 5% to 10% clay.

Confidence limits on the *mean*: $x \pm t \times s_x$ for (n–1) = 9 degrees of freedom:

$8 \pm (1.383 \times 0.73) = (7 \ldots 9)\%$

This is a very tight range. It means that, based on our sample, it is 80% probable that the true *mean* for Map Unit 1 lies in the range (7%…9%) clay.

Map unit 2: mean = 60, same s^2, *s*, s.e.; CV = 4%, C.I. for values = (56.8…63.2)%; C.I. for *mean* = (59…61)%.

The CV is quite low because the mean is high (60% clay) and the variance is low; this leads to a low *relative* variation. Note that in this example, the same variance (and hence the same width of the C.I.) led to two very different CV's, depending on the mean.

Other than the CV, the same comments hold as for MU1.

Question: is the C.I. for values of (56…63)% a narrow-enough range for interpretations? Probably it is; although clay can vary through a range of 7%, the difference in water & nutrient retention, stickiness & plasticity etc. may not be significant, since even at the lowest end of the range there is a lot of clay, and the upper end of the range is *proportionately* not much larger.

So we see that the CV in this case leads to a similar conclusion as a direct consideration of the C.I. (range of probable values).

The statistics confirm that we have **two well-defined map units**. In particular, since the C.I. for the two means do not overlap, we can conclude that the means are significantly different at the chosen probability level (80%); actually at 'any' level in this case. We can confirm this directly by a two-sample *t*-test, which gives a 99% confidence interval for the difference between the two means of (48.7…55.3), centered on the sample difference between means of 52%.

Situation 2: 'Incorrect' delineation

Now, compare this to the situation where we don't delimit the landforms correctly, but instead draw a line *across* the landscape (not respecting the soilscape), so that the two map units have equal numbers of observations from each landscape element. In other words, the line doesn't correspond to the soil differences. Can we tell this from the statistical analysis? Yes, here's how. Suppose our new line separate the same samples as follows:

(incorrect) Map unit 1: (4, 58, 6, 60, 8, 60, 8, 62, 10, 64); n = 10

(incorrect) Map unit 2: (56, 6, 58, 8, 60, 8 , 60, 10, 62, 12); n = 10

Let's examine these with a stem-&-leaf plot, this time with a step size of 10 (because there is such a wide range in both map units):

Map Unit 1	Map Unit 2
0 | 4 6 8 8	0 | 6 8 8
1 | 0	1 | 0 2
2 |	2 |
3 |	3 |
4 |	4 |
5 | 8	5 | 6 8
6 | 0 0 2 4	6 | 0 0 2

We can see by inspection that these **not** symmetrically distributed, they do **not** have a modal value in the middle of the distribution; the distributions are **bimodal** (two peaks). The median is by convention between the 5th and 6th values in order, (10 + 58)/ 2 = 34 and (12 + 56) / 2 = 34; but this value is not even close to any actual data value! The two distributions **overlap**. At this point we could stop and say that definitely the two map units do not separate clay content. But, for completeness, we continue the analysis with the sample statistics.

Calculating the sample statistics, we get:

Map unit 1: $x = 34$, $s^2 = 802.6$, $s = \sqrt{802.6} = 28.3$; $s_x = s / \sqrt{10} = 8.96$; CV = $s / x \times 100 = 83\%$

Confidence limits on the value:

$34 \pm (1.383 \times 28.3) = (-5.1 \ldots 73.1)\%$ which is so broad as to be absurd. It essentially means we can't say anything useful about a random sample within the (incorrect) map unit.

Confidence limits on *mean*:

$34 \pm (1.383 \times 8.96) = (21.6 \ldots 46.3)$

which is a very broad range. It means that, based on our sample, it is 80% probable that the true mean for Map Unit 1 lies in the range (21.6% … 46.3%) clay. This is not too useful.

Map unit 2: mean = 34, $s^2 = 710.2$, $s = 26.65$, $s_x = 8.43$; CV = 78%, C.I. value = $(-2.9 \ldots 70.9)\%$, C.I. *mean* = $(22.3 \ldots 45.7)$.

Both of these ranges are so wide as to be useless. The CV's also indicate such a high degree of variability within the map unit that they are surely non-homogeneous by any measure. We can see this with a simple histogram, which shows the bimodal distribution very clearly.

Conclusion: drawing a correct line to separate the 20 samples results in a dramatic increase in purity and a dramatic increase in the precision of predicting the mean value.

7.4.2 Using ANOVA to compute the effectiveness of a map

Moving on from the simple case of the previous §, we need a method to evaluate the effectiveness of the entire map in separating soil properties.

There is a simple method to determine the efficiency of a classification of the interval or ratio variables, and it is more-or-less valid for classified-interval or ratio, and for ordinal values: a **one-way Analysis of Variance** to compute the **percentage of total variance that is explained by the classes**.

The basic idea is: *Total-Variance = Within-Class Variance + Between-Class Variance*. The success of the map can be estimated by the ratio *Between-Class Variance / Total Variance*.

We will look first at ANOVA for continuous quantitative land characteristics (interval or ratio). This is taken largely from Webster & Oliver [61, pp. 63-71], with an example from terrain classification.

The simplest case is when we want to find out how well *one* variable (pH, clay content, plasticity limit…) is separated by the map. This is tested by sampling across the landscape, and classifying the samples according to the map unit in which they are located, and then analyzing this data by the technique now presented.

> Note: to get a correct estimate of the entire map, the sampling should be random across the whole map, i.e., not affected by the map. In practice this is quite rare, since sampling is usually purposeful, to characterize each map unit (e.g., by transect sampling). However, if all map units are sampled roughly in proportion to their area, the ANOVA is still valid.

If we use the subscript *W* to symbolize *within-class* and *B* to symbolize *between-class*, we can use the **intraclass correlation** r_i to estimate the effectiveness of the classification (i.e., map).

$$r_i = \frac{s_B^2}{s_B^2 + s_W^2}$$

The maximum value, in the case of a perfect map, is 1, which will occur if and only if the classes account for all the variance: s^2_B=1, s^2_W=0. The minimum value is 0, which will occur if there is no between-class variance: s^2_B=0; in this case the map provides no useful information. Here, the s^2 are population variances, where the population is all possible sample sites. Since we do not know the *population* variances, we have to *estimate* them (using the symbol s^2 for the estimates) from our *sample*. Let's see how this is done.

We can use one-way ANOVA, see e.g. Webster & Oliver [61, Table 4.1] and many other sources, to estimate these variances. Here the classes are the map units of the survey, so each observation falls in one class. From the ANOVA table we obtain the estimates:

> *B* : **between-class variance** (estimated by the **between**-class Mean Square)
>
> *W* : **within-class variance** (estimated by the **within**-class Mean Square)
>
> *T* : **total variance** (estimated by the **total** Mean Square)

Let's see how.

Consider a set of *N* data points (observations) *x* divided into *k* classes {1, 2, …, *i*, …, *k*}. These classes are the map units (strata). Each data point has a certain arbitrary numbering {1, 2, …, *j*, …, n_i} in its class *i*, so we can refer to the data point as x_{ij}., i.e. the j^{th} point in the i^{th} class (soil map unit).

The entire sample has some **total varianc**e; computed as the Total Mean Square *T*:

$$s^2_T = \frac{1}{N-1}\sum_{i=1}^{k}\sum_{j=1}^{n_i}(x_{ij} - \bar{x})^2 = T$$

This formula is the total mean square of all the observations. Note that the squared differences measure how far each observation is from the **grand mean**:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{k}\sum_{j=1}^{n_i} x_{ij}$$

Each class has a **within-class variance**:

$$s^2{}_i = \frac{1}{n_i - 1} \sum_{j=1}^{n_i} (x_{ij} - \overline{x}_i)^2$$

In this formula, the squared differences measure how far the observation is from the **class mean**:

$$\overline{x}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij}$$

We hope that the within-class variances are each less than the total variance, i.e., that each class is more homogeneous than the total sample.

Now, to evaluate the classification, we need to estimate the **total within-class variance**, i.e., combining the within-class variances of all the classes into one estimate. In many cases (and borne out by experience) we can make the **simplifying assumption** that **all classes have approximately the same variance**. Then we get an estimate of the **pooled within-class variance**:

$$s^2{}_W = \frac{1}{N - k} \sum_{i=1}^{k} \sum_{j=1}^{n_i} (x_{ij} - \overline{x}_i)^2 = W$$

Note that the squared difference attributed to an observation is now within its class. The denominator *(N - k)* is the number of degrees of freedom *not* taken by the classification system (i.e., the stratification). This is exactly the within-class mean square estimated by the ANOVA.

Finally, we want to estimate how much variance is removed by the classification. This is the **between-class** variance:

$$B = \frac{1}{k - 1} \sum_{i=1}^{k} (\overline{x}_i - \overline{x})^2$$

Here we see that the number of degrees of freedom taken by the classification system is ($k - 1$), i.e. one less than the number of classes. As a check, we add the total degrees of freedom: ($N - k$) + ($k - 1$) = $N - 1$ as expected.

The first thing we can do with this ANOVA an **F-test** on the ratio B/W with ($k - 1$, $N - k$) degrees of freedom. This tests the ratio of two variances, to see if they could have arisen by chance. If the F test is significant at some level *p*, we can conclude that the classification is statistically significant at that same level *p*. If not, no further analysis is justified. If yes (the common case), we want to estimate just how much information is gained by the classification.

A simple estimate of the variance *not* accounted for by the stratification is the ratio of the remaining within-class variance *W* to the total variance *T*. This is sometimes called the *relative variance* and is calculated as:

$$s_W^2 \big/ s_T^2 = W / T$$

In the ideal case, this would be 0, i.e. no variance is left within the classes. So, we **estimate the proportion of the variance *accounted for* by the classification** as the *complement* of this ratio:

$$1-\left(s_W^2 / s_T^2\right)=1-(W / T)$$

Adjusting the estimate

(This section can be omitted on first reading.)

This estimate (the complement of the relative variance) can be used for a first approximation to the success of the classification. However, it is usually not the end of the story.

According to Webster & Oliver, this estimate is only valid if the true class means μ_i are equal, in which case $\sigma^2_T = \sigma^2_W$ and these are estimated independently by s^2_T and s^2_W, i.e. T and W. In the case of soil map units it is quite unlikely that the means are equal, in fact we expect map units to have different means for most soil properties (that's why we separate them!).

If the means are not equal (the usual case), *B* as defined above estimates not only the between-class variance σ^2_w, but also a contribution from the between-class variance, specifically the sampling variances of the various class means. In other words, *B* is too large, so the actual success of the classification will be somewhat under-estimated. The true estimate of the between-class variance is:

$$s_B^2 = (B - s_W^2) / n_0$$

where s^2_W is estimated by *W*, and n_0 is a weighted average of the number of samples in each class:

$$n_0 = \frac{1}{k-1}(N - (\sum_{i=1}^{k} n_i^2 \Big/ N))$$

If there are the same number of samples *n* in each class (i.e., in each map unit), this reduces to just *n*.

With this estimate of the between-class variance *B*, we estimate the **intraclass correlation** by:

$$r_i = \frac{s_B^2}{s_B^2 + s_W^2} = \frac{B-W}{B+(n-1)W}$$

where the last expression comes directly from the ANOVA table. Recall (from the beginning of this section) that this will be 1.0 for a perfect classification, 0.0 for a useless classification.

It is probably not yet obvious why we have to adjust the relative variance in the case that the class means are not equal: We can see why this is necessary with a simple example. Suppose there are just two classes with widely-separated mean. Using the same 'cooked' data from the two-map unit example above, we get the following ANOVA table:

SOURCE	DF	SS	MS	F	p
classes	1	13520.00	13520.00	2112.50	0.000
ERROR	18	115.20	6.40		
TOTAL	19	13635.20	717.64		

Using the terminology of this section, we have *T* = 717.64; *B* = 13,520; *W* = 6.4. The relative variance is *W / T* = 0.89%, which extremely low, so by the naive measure, the classification explains 99.11% of the total variance. However, using the intraclass correlation, we have *r* = 1.0, which is in fact correct;

the classes explain *all* the difference, because there is no overlap between them. In this case, the correction is minimal.

7.4.3 Multivariate classification

A much more complicated situation is when we want to see how well the map separates soils in *multi-variable* space, i.e., considering all the relevant variable together. One way is to evaluate for a number of variables separately, and compute a composite measure, e.g. average r_i. But this ignores correlations between variables. So, a better method is to use multivariate statistical techniques. The interested reader is referred to Webster & Oliver [61], Chapters 7 to 9.

The user's criterion: How well is the land performance separated by the map?

Looking at the user's point of view, Byrd [16] states "The test of accuracy is, and should be, this: does [the soil survey] convert to an interpretive map satisfactorily?". In other words, the user doesn't particularly care if we have produced a pedologically-correct map; the user's interest is in the interpretive map *for a particular land use*.

So, we can use the same techniques from the user's point of view. Here the variable is some *response*, e.g. crop yield, earliest tillage date, … in which the user is interested. This response has to be measured at many points and classified by map unit, then the ANOVA can be applied as above.

Complication: the response, such as crop yield, may also be influenced by variables that were not measured in the soil survey. In particular: climate & management. One way to analyze this is by a **multi-way ANOVA**, using climate regions, management levels, and finally soil classes, as factors.

This analysis is interesting in other ways. In particular, it shows which factors are most important for the response. In some cases the soil might be very important, in others not at all. Even if another factor is dominant, the soil classes may vary significantly within one or more classes of the other factor. Also, the **interaction term** of the ANOVA can show whether the different soil classes behave differently in different classes of the other factor. Example: soils with high water retention / slow conductivity vs. soils with low water retention / high conductivity, compared in very wet and very dry climates. This should show a strong interaction effect for rainfed crop yield.

7.5 Methods for evaluating the accuracy of a soil survey

This section is somewhat speculative; however I think it has promise. It is an attempt to apply to soil survey, accuracy assessment methods borrowed from land cover classification

The basic idea is to compare the predicted classification of each site with the actual classification as discovered by *ground truth*. A good review of methods in the context of vegetation classification is given by [17]; the same techniques can be applied to evaluating soil surveys.

Four kinds of accuracy information:

1. *Nature* of the errors: what kinds of information are confused?

2. *Frequency* of the errors: how often do they occur?

3. *Magnitude* of errors: how bad are they? E.g., confusing old-growth with second-growth forest is not as 'bad' an error as confusing water with forest; confusing similar soils (i.e. that share class limits) is not as 'bad' an error as confusing very different soils.

4. *Source* of errors: why did the error occur? This allows us to refine the survey methodology.

<u>The Confusion Matrix</u>

The analyst selects a sample of mapped points (pedons) and then visits the sites (or vice-versa), and builds a *confusion matrix*. This is used to determine the *nature* and *frequency* of errors.

Definitions:

columns = ground data (assumed 'correct')

rows = map data (classified by the mapping procedure)

cells of the matrix = count of the number of observations for each (ground, map) combination

diagonal elements = agreement between ground and map; ideal is a matrix with all zero off-diagonals

errors of omission (map producer's accuracy) = incorrect in column / total in column. Measures how well the map maker was able to represent the ground features. A low producer's accuracy means that the producer missed (did not map) a class that is actually present in the landscape.

errors of commission (map user's accuracy) = incorrect in row / total in row. Measures how likely the map user is to encounter correct information while using the map. A low consumer's accuracy means that user looking for a particular class as it was mapped will not find that class at the points in the landscape where it is predicted to occur.

Overall map accuracy = total on diagonal / grand total

A statistical test of the classification accuracy for the whole map or individual cells is possible using the *kappa* index of agreement. This is like a χ^2 test except that it accounts for chance agreement, i.e. the possibility that we have a correct classification merely by chance. This is like correcting the mark on a test made up of true/false question to account for the fact that we expect 50% score if the student simply answers each question at random. A nice introduction to this statistic is by Lillesand & Kiefer [42, , p. 616-617].

Conceptually, *kappa* may be defined as:

$$\hat{k} = \frac{observed\ accuracy - chance\ agreement}{1 - chance\ agreement}$$

It is calculated from the confusion matrix as:

$$\hat{k} = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} x_{+i})}$$

where r is the number of rows (& therefore columns) in the matrix, x_{ii} is the count in a diagonal cell where row and column i meet (i.e., correct classifications), x_{i+} is the row total, x_{+i} is the column total, and N is the total number of observations.

Sample confusion matrix

		Ground			
		A	B	C	*Total*
Map	A	**10**	**2**	**3**	*15*
Classification	B	**0**	**20**	**0**	*20*
	C	**4**	**1**	**10**	*15*
	Total	*14*	*23*	*13*	*50*

Overall *accuracy*: (10+20+10)/(10+2+3+0+20+0+4+1+10)= 40/50 = 80%

Accuracy estimated by *kappa*:

$$\hat{k} = \frac{50 \cdot (10 + 20 + 10) - ((14 \cdot 15) + (20 \cdot 23) + (15 \cdot 13))}{(50)^2 - ((14 \cdot 15) + (20 \cdot 23) + (15 \cdot 13))} = \frac{2000 - 865}{2500 - 865} = 0.694 = 69.4\%$$

Note that this is quite a bit lower than the naive accuracy assessment. It is a more reliable measure of how good the accuracy really is. In addition, *kappa* can be tested for significance by various statistics.

Error of *commission* for class A: (2+3)/(10+2+3) = 5/15 = 33% error; in this proportion of space that is mapped in class A, the map user will *not* find the mapped class actually on the ground.

Error of *omission* for class A: (0+4)/(10+0+4) = 4/14 = 29% error; in this proportion of space actually occupied by class A, the map user who finds this class on the ground will *not* see it accurately represented on the map.

Complication: compound map units

What if more than one soil is named for a map unit?

Approach 1: Accept any named soil as ‘correct’.

Approach 2: Insist on correct proportions.

Fuzzy accuracy assessment

There is a fundamental problem with the confusion matrix: the ground data may not be just ‘correct’ but ‘somewhat correct’... a problem of classification. [32] provide a good introduction to this problem and to the use of fuzzy sets to solve it.

Basic idea: an expert can classify ground truth using *linguistic variables* on a scale of 1-5: (1) absolutely wrong, (2) understandable but wrong, (3) reasonable, acceptable but there are better answers, (4) good answer, (5) absolutely right. Then the confusion matrix is expanded to answer two more precise questions:

(1) How frequently is the map category the best possible choice?

(2) How frequently is the map category acceptable?

Various fuzzy measures of correctness can be constructed to answer these questions.

In the context of soil survey, answer (5) means that the map and ground observation are in the same class; (4) that they are different but similar classes, with only minor differences, (3) that they are in different and dissimilar classes, separated by one class limit, etc.

A *fuzzy set A* over a universe of possible members *X* consists of members, a generic member being labeled as , along with a *membership grade* for each member *x*, defined either by enumeration or by a function:

$$A = \{(x, m_A(x)) | x \in X\}$$

where the membership function $0 \leq m_a(x) \leq 1$. Intuitively, 1 = totally in the set, 0 = totally not in the set. Traditional *crisp* sets only allow values of 0 or 1, corresponding to *false/true*, *out/in*, *wrong/right* etc.

In the context of map accuracy assessment:

X is the set of evaluation sites, i.e., polygons or pixels where we will compare the mapped and actual values.

There is a separate fuzzy set A_C for each class $c \in C$, where *C* are the classes, e.g. for a set of six possible soil series *C* = {"Norfolk", "Goldsboro", "Lynchburg", "Rains", "Wagram", "Pantego"}. Note that this implies that a given site can be assigned to *more than one class*, with varying degrees of correctness. This recognizes that the absolute boundaries of Soil Taxonomy or series are not always precisely-measurable.

Suppose we have five accuracy evaluation sites: *X* = {a, b, c, d, e}

Then for the Norfolk series we might have $A_{Norfolk}$ = {(a,.5), (b,0), (c,1), (d,.75), (e,.25)}, where the linguistic scale 1-5 has been transformed to a membership scale 0, ..25, .5, .75, 1. So site 'b' is absolutely not the Norfolk series, site 'c' is undoubtedly the Norfolk series, if site 'd' were classified as Norfolk it would be a good but not ideal answer, etc.

We can see how close these sites are to other series, e.g. $A_{Goldsboro}$ = {(a,.75), (b,.25), (c,.75), (d,1), (e,.5)}.

To measure the *magnitude* of errors, we can define a function to be evaluated at each site *x*:

$$\Delta(x) = m_{c(x)}(x) - \max_{C \in \mathbf{C}, C \neq c(x)} m_C(x)$$

where $-4 \le \Delta(x) \le +4$, if the linguistic variables range from 1 to 5. ±4 indicates maximum deviation, 0 is perfect agreement. These scores can be used to weight the confusion matrix or compute other functions.

Question: (1) How frequently is the map category the best possible choice?

Answer: Define:

$$MAX(x,C) = \begin{cases} 1 & \text{if } m_x(x) \ge m_{c'}(x), \forall c' \in \mathbf{C} \\ & 0 \text{ otherwise} \end{cases}$$

> I.e., *MAX(x,C)* is 1 iff C is the best answer among the answers given. Then use *MAX* in the confusion matrix.

Question: (2) How frequently is the map category acceptable?

Answer: Define:

$$RIGHT(x,C) = \begin{cases} 1 & \text{if } m_x(x) \ge t \\ 0 \text{ otherwise} \end{cases}$$

where τ is the *threshold* of 'correctness', selected by the expert to correspond to 'good enough'. Then use *RIGHT* in the confusion matrix. In soil survey, we might define τ to be 0.75, i.e. the series are similar.

7.6 Guidelines for evaluating the adequacy of SRI

How can a **consumer** of soil survey information decide if an existing work is satisfactory or **adequate** for the consumer's needs?

This was the subject of quite some work in late 1970's and early 1980's leading to workshops at Cornell University in 1977 and 1978, and a monograph summarizing the conclusions of these workshops, and detailing a methodology to evaluate the adequacy of soil surveys, which I largely wrote in 1982 [31]. This is essentially a consumer's-eye view of many of the concepts we have previously discussed.

Purpose: allow external evaluation of the value of soil survey

There are four components of adequacy:

1. Map scale & texture

2. Map legend

3. Base map quality

4. Ground truth

8 Survey specification & planning

The survey must be cost-efficient; we need a good plan so that funding and logistics will be sufficient to carry out the survey. In this unit we discuss survey phases, survey planning, and cost effectiveness..

General references: [62], [25], [40], [33], [48], [24, Ch 2 & 4]

In general terms, the **steps** in a typical soil survey are as follows:

1. **Needs assessment**: Who needs the survey and why?
2. **Planning, terms of reference**: Scale, type of map units, intensity of observations, schedule, personnel…
3. **Research**: Existing information (soils, geology, climate, vegetation, land use…)
4. **Pre-mapping**: Preliminary API, selection of sample areas, detailed mapping in sample areas, decision on legend categories
5. **Field mapping**: Complete coverage of survey area, additional sampling.
6. **Quality control**, including **correlation**
7. **Cartography**: transfer to geometrically-correct base, map publication
8. **Interpretation** & land evaluation
9. **Reporting**: Descriptive legend, interpretive tables, classification & correlation
10. **Soil Geographic Database**, including **GIS layers**
11. **Publicity**

8.1 Needs assessment

Before any serious plan for survey can be made, we need to know **who** needs soil information, **for what purposes**, and from that we can determine the **type** and **detail** of information that is required, as well as the **form** of the output.

Soil survey is demand-driven. Two cases:

(1) Special-purpose: one application, short time period of applicability

(2) General purpose: many applications, long time period of applicability

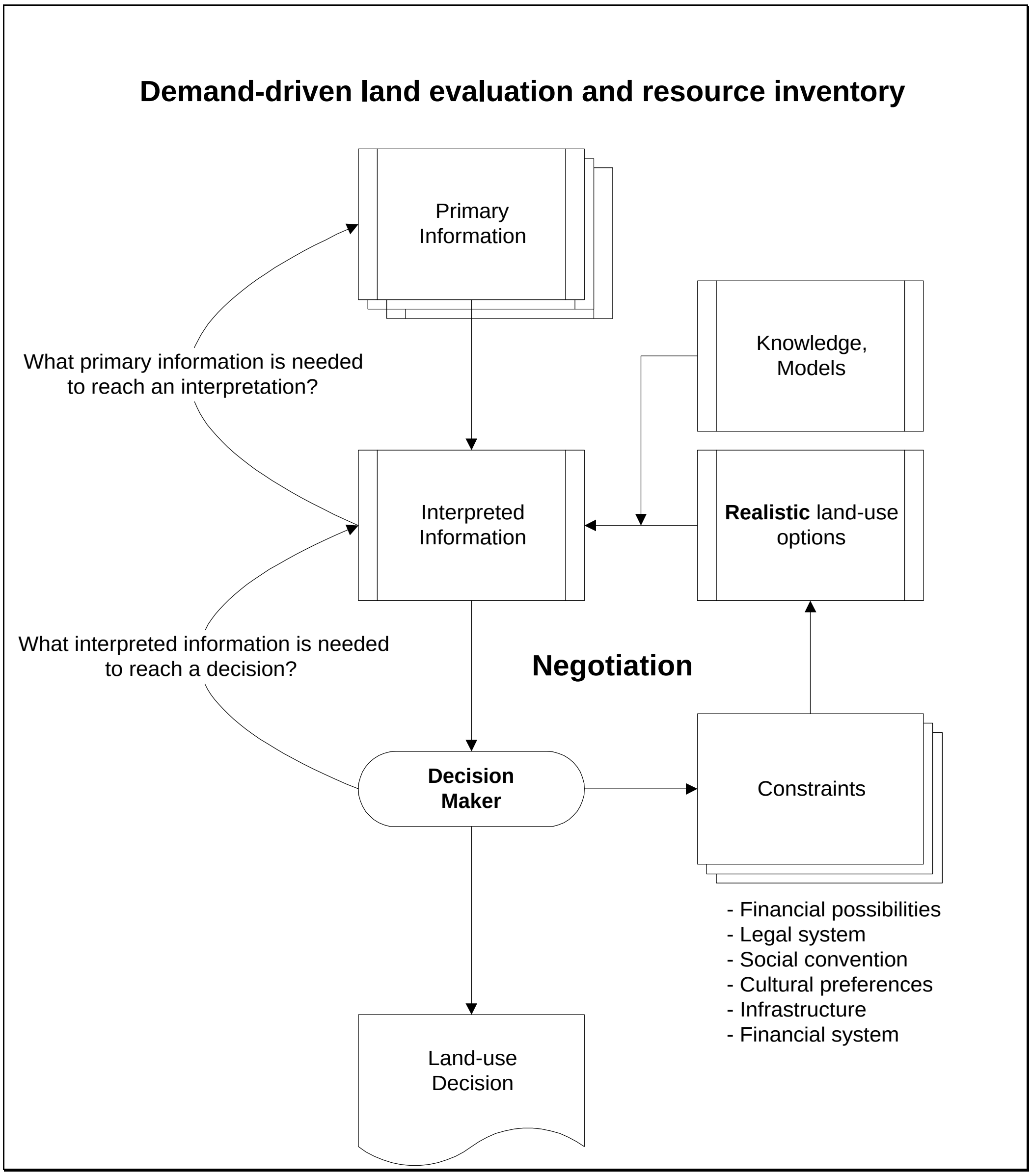
In this phase, **we imagine how the soil survey would be applied**. If we can visualize who would use the soil survey, and for what, we can decide what information would be needed.

In particular, if the survey is to be used in land evaluation or land use planning (and why would we do the survey otherwise?), we need to know the **size of decision areas** (MDA) of various potential users.

The purpose of the survey also dictates, in part, the categorical detail of the mapping legend, the choice of phases, and if any special information should be collected in the field. For example, if the survey is to support irrigation projects, we will need information on infiltration, leaching requirement, salts etc.

The **output** of this phases is a detailed **Memorandum of Understanding** (MOU), sometimes called **Terms of Reference** (TOR), which is essentially a **contract** for the soil survey between the surveying organization and the client. Even if both are part of the government, it is good to have an explicit contract.

8.1.1 Flow of information in planning a soil survey



8.2 Terms of Reference

Some items in this contract:

1. Anticipated users & uses of the soil survey (why is it being done?)
2. Scale
3. Type of map units
4. Intensity of observations; Number of detailed / rapid soil observations; whether all delineations are to be visited; transects or other quality control methods
5. Form & scale of published map (paper, digital…)
6. Contents of the report: map unit descriptions
7. Kinds of interpretations to be included in the report
8. How scientific quality is to be ensured: field and office review procedures
9. Personnel, logistics (vehicles, access…)
10. Schedule, checkpoints along the way
11. Budget

8.3 Specific issues in survey specification & terms of reference

References: [25, 40, 62].

8.3.1 Choice of map scale

The publication map scale determines the intensity of observations, the type and purity of the map units, and to great extent the cost and usefulness of the survey. Careful consideration should be given to the scale. In some organizations or for certain projects the scale is pre-specified; this is a mistake and should be evaluated for each soil survey objective and soil landscape.

We can trade map scale (= observation intensity) for map unit purity; categorical detail (precision of map unit definitions) requires corresponding cartographic detail (number of delineations in a given land area)

Suggested procedure:

1. Determine the **Minimum Decision Area** (MDA) for the potential uses of the soil survey, and from this compute the first proposed scale (i.e. the degree of **cartographic detail**). The cartographic concept corresponding to the MDA is the Minimum Legible Delineation (MLD); we require that the MDA = MLD converted to ground scale. Recall that for the Minimum Legible Delineation

(MLD) defined as 0.4cm^2, the formula is SN = [√(MDA, ha x 250)] x 1000. E.g. for MDA = 1.6ha, the formula gives SN = 20 000, so the scale required is 1:20 000. Call this the **decision scale**.

2. Compute the **number of observations** that would have to be made to achieve this intensity. Recall that there is one observation per 2.5 to 10 MDAs (using a 0.4cm^2 MLD); i.e. one observation per 1 to 4cm^2 on the published map. In this example, we require 1 observation per 4 to 16ha.

   If the decision scale is too large (i.e. we do not have enough resources), we have two choices:

   2.1. **Map at the decision scale** using **sample areas** to concentrate the observations, and **extrapolate** to other, unvisited areas. Make sure to show the map user which areas were actually visited! If the basis of extrapolation is correct (e.g. geo-pedological approach) and correctly applied, this can result in the coverage of a much wider area with the same effort.

   2.2 **Map at a smaller scale** with a **two-stage** map, i.e. one that has to be interpreted by the user in the field in order to find their MDAs. So we take the decision to map **associations** at the chosen level of categorical detail (see next point).

3. Determine the degree of **categorical detail** required to meet the survey objectives, i.e., **how specific are the interpretations that have to be made**? Express this either as **ranges of soil properties** allowed in each category, or as a hierarchical **level in a classification system** (if appropriate). For example, for interpretations for grassland we may require only that soils be classified as having high, medium or low water-holding capacity; for interpretations for groundwater contamination by heavy land applications of manures, we may require detailed information on the moisture-release curve as required by a soil-water-chemical model. Some projects specify 'map units must be consociations of soil families' etc.; presumably they have already determined that this level of categorical detail is needed.

4. **<u>Now we try to match the required cartographic and categorical detail</u>**. From a **preliminary study of the soil pattern** (perhaps extrapolating from similar areas), determine what is the **natural scale** required to separate soils at the **required categorical detail in the survey area**, i.e. at what scale would the Average Sized Delineation (ASD) be 4xMLD = 1.6cm^2 on the map? This is determined from the Average Sized Area (ASA) in a map that shows the required categorical detail. Calculate the corresponding scale with the formula SN = [√(ASA/4, ha x 250)] x 1000.

   For example, if the ASA of a map of phases of soil series is 12ha, calculate SN = [√(12/4, ha x 250)] x 1000 = 27,386; the map must be at least approx. 1:27 500 to show this natural scale legibly

   (This can also be calculated directly: 12ha = 120 000m^2 = 1'200 000 000cm^2, the map must have a scale of at least 1.6cm^2 / 1'200 000cm^2 = 1:750 000 cm^2 $(\text{cm}^2)^{-1}$ = 1:√750 000 cm cm^{-1} = 1:27 386.)

   There is no substitute for this step! The natural scales at a given categorical level vary widely. Example from East Anglian fens [24, Plate 1] where very contrasting soil series vary over such a small scale that a 1:2 500 map or larger would be required to separate them, vs. the same amount of categorical contrast in a broad erosional landscape.

   Note that if the decision has been made for a **two-stage** map (i.e. of associations) we find the **natural scale of associations**, not simple map units.

Soil variability studies in many landscapes have shown that a scale of at least 1:25 000 is required to map mainly consociations of phases of soil series [1, Ch. 2], and at least 1:100 000 to map mainly associations of phases of three or fewer soil series.

5. If everything has gone well, the natural scale = decision scale, and the number of observations is not too high; we have reached a decision. If not, there are several alternatives, depending on the nature of the discrepancy.

Case 1: **The natural scale is smaller than the decision scale**, i.e. the soil pattern does not require so detailed a map as the decision scale.

Solution 1: Map at the smaller scale, i.e. the natural scale. The user will have sufficient information even though the MLA on the published map will be larger than the MLA corresponding to the MDA.

Solution 2: Map at the decision scale anyway; the published map will have a large IMR. The only drawbacks are that the map uses more paper than necessary, and the map user can not grasp the soil pattern in one view.

Case 2: **The decision scale is smaller than the natural scale**, i.e. the soil pattern occurs at a finer pattern than the decision maker will use.

Solution 1: Map at the decision scale, and use compound map units; either complexes or associations according to the soil pattern. Describe the spatial pattern of the soils within the compound map units. The map user will have to decide how to treat the map unit as a whole, taking into account its constituents. For example, wet spots that occur as isolated patches require spot drainage; but they can easily be identified in the field.

Solution 2: Ask for a larger budget. Explain to the client that the alternative is a two-stage map.

8.3.2 Type of map unit

This is closely related to the map scale. At a given scale, the soilscape dictates the purity of the map units (see previous section).

8.3.3 Intensity of observations

This is related to map scale, as well as national standards. As explained above (§3.1.8), a common requirement for soil survey [62, Table 3.3] is that there be, **on average, from ¼ to 1 field observation per cm^2 of *map***, i.e. each observation represents from $1 cm^2$ to $4 cm^2$. But this can be higher or lower. The contract may state total number of observations, or observations per cm^2 of map, or per km^2 of ground at the proposed scale.

8.4 Research phase

Collect all relevant information on the study area:

1. Cartographic: especially a reliable base map

2. Thematic: anything that affects soil formation, e.g. geology, geomorphology, vegetation, land use

3. Theoretical: soil formation, geomorphology

8.5 Initial mapping

The purpose of this step is the **understand the soil pattern** and to **establish a mapping legend** for the routine-mapping stage.

1. Preliminary API; tentative geopedological legend.

2. Selection of sample areas

3. Detailed mapping in sample areas

   Generally at 2x mapping scale (i.e. areas are magnified 4x); maybe even 4x mapping scale.

   Uses a more detailed legend, allows estimating map unit composition

   The idea is to really understand typical soil landscapes

   Can make block diagrams and cross-sections of landscapes

4. Decision on legend categories

5. Develop a **field key**

8.6 Routine mapping

Complete coverage of survey area using the field key, additional sampling.

API lines may be adjusted, API units may be combined or split based on soils actually found.

ITC semi-detailed approach: extrapolation to similar API units, not every unit is visited, but the landscape correspondence must be checked.

8.6.1 Data organization in the field

Soil survey is first of all a set of scientific observations! and secondly an interpretation of these observations into a coherent theory of pedogenesis and soil geography. As in any scientific investigation, we must keep accurate and complete **field notes**.

Standard forms to record observations; standard terminology.

Always have an **'exact' location**: (1) GPS, (2) on airphoto (can prick through to the back and circle)

Standard numbering scheme.

Field notebook for observations; what seems minor today may be major tomorrow! Be a good observer in the field. Clearly distinguish between observations and interpretations (e.g. of pedogenesis, geomorphology…). Note correlations with land use for the land evaluation phase.

Always keep original documentation!

8.7 Quality control, including correlation

A major problem as soon as there are several mappers is quality control and correlation (see section on correlation and QC, previous).

Quality control: is the work done correctly?

Correlation: are terms and concepts used consistently?

Progress reviews

Final review: adjust legend if necessary

8.8 Cartography

Transfer to geometrically-correct base

Map publication

8.9 Interpretation & land evaluation

According to the Terms of Reference.

These tables will be most used by the clients.

The basic idea is: one soil map, many interpretations, using the legend categories as the ‘information carriers’.

8.10 Reporting

Descriptive legend

Interpretive tables

Soil classification & correlation

8.11 GIS & Soil Database

Ideally, this is done as an integral part of the mapping and reporting. See separate lecture notes on this topic.

8.12 Publicity

An unpublicized soil survey is a waste of time and money. From the beginning of the project it should be decided how to disseminate the results.

Standard channels: government offices, libraries, extension offices

Also: schools, producer's cooperatives, professional associations (e.g. highway engineers)

8.13 Cost-effectiveness of soil survey

The soil survey should not be undertaken if the total benefits do not exceed the total costs. The costs are easy to quantify after the fact, and fairly easy to predict, at least within an order of magnitude, before the survey begins. The benefits are harder to quantify: first, the survey may have many users, second, the benefits may be spread over a long time, and third, some of the benefits may be difficult to quantify (e.g., environmental protection).

8.13.1 Cost

Western [62] summarizes earlier work by Bie & Beckett, which developed general relations between mapping scale (expressed as the scale number, SN) and cost, as well as between mapping scale and map intricacy. Obviously, these are only guidelines, and should be modified for areas with unusually intricate or complicated soil patterns, unusually easy or difficult access, unusually easy or difficult sampling, etc. But they give some ideas about the magnitude of the effort required.

First [5], they studied ten surveys worldwide, at different scales, and established that effort *E*, measured in person-days $(km^2)^{-1}$, is linearly related to SN, on a log-log scale. The relation is approximately:

$$\log_{10} E = 7.41 - 1.57 \times \log_{10} SN$$

with a correlation coefficient of approximately 72.25%, which is surprisingly high considering the different terrain, logistics, soil patterns, etc.

For example, a 1:50 000 survey (SN = 50 000, $\log_{10}$ SN = 4.7) should require $\log_{10} E = 3.25\times10^{-2}$, so $E = 1.08$ man-days $(km^2)^{-1}$. In other words, to make a soil survey at 1:50 000 should take about 1 man-day per km². So one map sheet of the Netherlands (20×25km = 500km²) would required about 460 man-days; a party of four surveyors should be able to do the job in 115 days (about four months).

What happens as we increase the scale? Naively, we would expect that halving the scale would increase the survey effort by a factor of $2^2 = 4$; however, some of the fixed and especially transport costs do not increase so much. The equation gives for 1:25 000 scale survey an effort of 3.2 man-days $(km^2)^{-1}$, almost exactly 3 times as much (rather than 4). In fact, the factor *F* predicted by the equation is: $\log_{10} F = -1.57 \times \log_{10} (½)$, i.e. $F = 2.97$.

Bie & Beckett [5] also quantified the intricacy of the soil pattern mapped at any scale, and found a very similar relation. They counted the number of boundary lines crossed per 1km traverse *I*, and found the relation:

$$\log_{10} I = 4.22 - 0.88 \log_{10} SN$$

with a correlation coefficient again of approximately 72.25%, which is surprisingly high considering the different soil patterns. This strongly implies that mappers have an intuitive concept of a ‘pleasing’ map pattern than can be shown at a given scale, and adjust their categorical concepts accordingly.

For example, at 1:50 000, a 1km traverse would be expected to cross approximately 1.2 soil boundaries (i.e., boundaries would be spaced every 825m); at 1:25 000 it would cross approximately 2.2 boundaries (i.e., boundaries would be spaced every 445m); at 1:12 500, 4.1 boundaries (spacing 240m).

To calculate the **total costs**: Multiply the predicted effort by the cost per man-day, including support services (driver, field assistants etc.) and transport. Add laboratory analyses and any special sampling needs. The book by Western has much more practical information on survey costing.

8.13.2 Benefits

The benefits of soil survey are harder to quantify: first, the survey may have **many users**, second, the benefits may be spread over a **long time**, and third, some of the benefits may be **difficult to quantify** (e.g., environmental protection).

For a good review of this subject, see Western [62], Chapter 8.

The **benefits** of soil survey are actually the benefits of various kinds of **land use decisions** (strategic: land allocation; tactical: land management) that are **improved** as the result of the **stratification** of the landscape, and then the **site-specific predictions** made by the soil survey.

Example: Without a soil survey, consulting agronomists (e.g., extensionists) make a single fertilizer recommendation for the whole area. With a soil survey, different recommendations are made for different soil types. The direct economic benefits are of two kinds: (1) saving fertilizer, i.e. using a lower than average dose, in those cases that the extra fertilizer would not cost-effectively increase crop yield; (2) adding more fertilizer than the average recommendation if it is cost-effective in increasing crop yield. Also there may be an indirect benefit in this case: less ground-water contamination by leached fertilizer.

Some examples are more site-specific, but can save lots of money. Example: selecting a site for a new development, sanitary landfill, industrial park etc.

The question is: what exactly are the potential benefits? And, will they be realized? In other words, will decision-makers use the results? Will they even know about them? **An unpublicized soil survey has no benefit!**

Note that there are two components: (1) stratification and (2) prediction (interpretation). Someone has to do the interpretation! **An uninterpreted soil survey has no benefit!**

9 Bibliography

1. Avery, B.W., *Soil survey methods: a review*. Technical Monograph No. 18. 1987, Silsoe: Soil Survey & Land Resource Centre. 86.

2. Baize, D. and M.C. Girard, eds. *Référentiel pédologique 1995*. . 1995, Institut National de la Recherche Agronomique: Paris. 332.

3. Beckett, P.H.T., *Method and scale of land resource survey, in relation to precision and cost*, in *Land evaluation: Papers of a CSIRO Symposium, organized in cooperation with UNESCO, Canberra 26-31 August 1968*, G.A. Stewart, Editor. 1968, Macmillan Company of Australia: South Melbourne. p. 53-63.

4. Beckett, P.H.T. and P.A. Burrough, *The relation between cost & utility in soil survey. IV. Comparison of the utilities of soil maps produced by different survey procedures, and to different scales.* Journal of Soil Science, 1971. **22**(4): p. 466-480.

5. Bie, S.W. and P.H.T. Beckett, *The costs of soil survey.* Soils and Fertilizers, 1970. **33**: p. 203-216.

6. Breeuwsma, A. and H.d. Bakker, *Bodemvorming*, in *Bodemkunde van Nederland*, H.d. Bakker and W.P. Locher, Editors. 1990, Malmberg: Den Bosch. p. 57-70.

7. Bregt, A.K., *Processing of soil survey data*, . 1992, Wagenigen Agricultural University: Wageningen, the Netherlands. p. x + 167.

8. Bridges, E.M., N.H. Batjes, and F.O. Nachtergaele, eds. *World reference base for soil resources : atlas*. . 1998, ACCO: Leuven. 79.

9. Brown, A. and W. Feringa, *A colour handbook for GIS users and cartographers*. 1999, Enschede, NL: International Institute for Aerospace Survey and Earth Sciences (ITC). 94.

10. Brown, R.B. and J.H. Huddleston, *Presentation of statistical data on map units to the user*, in *Spatial variability of soils and landforms*, M.J. Mausbach and L.P. Wilding, Editors. 1991, Soil Science Society of America: Madison. p. 127-147.

11. Brubaker, S.C. and C.T. Hallmark, *A comparison of statistical methods for evaluating map unit composition*, in *Spatial variability of soils and landforms*, M.J. Mausbach and L.P. Wilding, Editors. 1991, Soil Science Society of America: Madison. p. 73-88.

12. Buol, S.W., F.D. Hole, and R.J. McCracken, *Soil genesis and classification*. 3rd ed. 1989, Ames, IA: The Iowa State University Press. xiv, 446.

13. Burrough, P.A., *Principles of geographical information systems for land resources assessment*. 1986, New York: Oxford University press. xiii, 193.

14. Burrough, P.A., *Sampling designs for quantifying map unit composition*, in *Spatial variability of soils and landforms*, M.J. Mausbach and L.P. Wilding, Editors. 1991, Soil Science Society of America: Madison. p. 89-125.

15. Butler, B.E., *Soil classification for soil survey*. Monographs on soil survey, ed. R.W.a.V.C.R. P.H.T. Beckett. 1980, Oxford: Oxford Science Publications. 129.

16. Byrd, H., *Speaking out on soil survey (letter to the editor).* Soil Survey Horizons, 1991. **32**(4): p. 126-127.

17. Congalton, R., *A review of assessing the accuracy of classifications of remotely sensed data.* Remote Sensing of Environment, 1991. **37**: p. 35-46.

18. Cremeens, D.L., R.B. Brown, and J.H. Huddleston, eds. *Whole regolith pedology*. SSSA Special Publication 34. 1994, Soil Science Society of America: Madison, WI. 136.

19. Daniels, R.B., *et al.*, *Soil systems in North Carolina*. North Carolina Agricultural Research Service Bulletin 467. 1984, Raleigh, NC: North Carolina Agricultural Research Service. 77.

20. Davis, R.E., *et al.*, *Surveying: Theory and Practice*. 6th ed. 1981, New York: McGraw-Hill. xv, 992.

21. de Gruijter, J.J., *Numerical classification of soils and its application in survey*. Agricultural Research Reports. Vol. 855. 1977, Wageningen: PUDOC.

22. de Gruijter, J.J. and B.A. Marsman. *Transect sampling for reliable information on mapping units*. in *Soil spatial variability: proceedings of a workshop of the ISSS and SSSA*. 1984. Las Vegas: PUDOC.

23. Deckers, J.A., F.O. Nachtergaele, and O.C. Spaargaren, eds. *World reference base for soil resources : introduction*. . 1998, ACCO: Leuven. 165.

24. Dent, D. and A. Young, *Soil survey and land evaluation*. 1981, London, England: George Allen & Unwin. xiii, 278.

25. EUROCONSULT, *Agricultural Compendium for rural development in the tropics and subtropics*. 1989, Amsterdam: Elsevier. 740.

26. Eyk, J.J.v.d., C.N. MacVicar, and J.M.d. Villiers, *Soils of the Tugela Basin: a study in subtropical Africa.* Natal Town & Regional Planning Reports 15. 1969, Natal (RSA): Natal Town & Regional Planning Comission. 263.

27. FAO, *Report on the Agro-ecological zones project*. World Soil Resources Report 48. Vol. 1: Methodology and results for Africa. 1978, Rome: Food and Agriculture Organization of the United Nations. xi, 158.

28. FAO, *Guidelines: land evaluation for rainfed agriculture*. Soils Bulletin 52. 1983, Rome, Italy: Food and Agriculture Organization of the United Nations.

29. FAO, *Agro-ecological assessments for national planning : the example of Kenya.* FAO Soils Bulletin 67. 1993, Rome: Food and Agriculture Organization of the United Nations. x, 154.

30. FAO, *World reference base for soil resources*. World Soil Resources Report 84. 1998, Rome: Food and Agriculture Organization of the United Nations. vii, 88.

31. Forbes, T.R., D. Rossiter, and A. Van Wambeke, *Guidelines for evaluating the adequacy of soil resource inventories*. 1987 printing ed. SMSS Technical Monograph #4. 1982, Ithaca, NY: Cornell University Department of Agronomy. 51.

32. Gopal, S. and C. Woodcock, *Theory and methods for accuracy assessment of thematic maps using fuzzy sets.* Photogrammetric Engineering & Remote Sensing, 1994. **60**(2): p. 181-188.

33. Gunn, R.H., *et al.*, eds. *Australian soil and land survey handbook: guidelines for conducting surveys*. . 1988, Inkata Press: Melbourne. 300.

34. Heuvelink, G.B.M., *Error propagation in quantitative spatial modelling: applications in Geographical Information Systems*. Netherlands Geographical Studies 163. 1993, Utrecht: Faculteir Ruimtelijke Wtenschappen Universiteit Utrecht. 151.

35. Hoaglin, D.C., F. Mosteller, and J.W. Tukey, eds. *Understanding robust and exploratory data analysis*. . 1983, Wiley: New York. 447.

36. Holmgren, G.C.S., *The Point Representation of Soil.* Soil Science Society of America Journal, 1988. **52**: p. 712-716.

37. Holst, A.F.v., *Bodemkartering en bodemkaarten*, in *Bodemkunde van Nederland*, H.d. Bakker and W.P. Locher, Editors. 1990, Malmberg: Den Bosch. p. 85-99.

38. Knox, E.G., *Soil individuals and soil classification.* Soil Science Society of America Proceedings, 1965. **29**: p. 79-84.

39. Lagacherie, P., P. Andrieux, and R. Bouzigues, *Fuzziness and uncertainty of soil boundaries: from reality to coding in GIS*, in *Geographic objects with indeterminate boundaries*, P.A. Burrough and A.U. Frank, Editors. 1996, Taylor & Francis: London. p. 275-286.

40. Landon, J.R., ed. *Booker tropical soil manual : a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. . 1984, Longman: New York. xiv, 450.

41. Lepsch, I.F., *et al.*, *Manual para levantamento utilitário do meio físico e classificaçao de terras no sistema de capacidade de uso.* 4ª aproximaçao ed. 1991, Campinas, SP: Sociedade Brasileira de Ciencia do Solo. 175.

42. Lillesand, T.M. and R.W. Kiefer, *Remote sensing and image interpretation*. 3rd ed. 1994, New York: John Wiley & Sons. xvi, 750.

43. Olson, G.W., *Soil survey interpretation for engineering purposes*, . 1973, FAO.

44. Olson, G.W., *Soils and the environment*. 1981, New York: Chapman & Hall. 178.

45. Robinson, A.H., *et al.*, *Elements of cartography*. 6th ed. 1995, New York: John Wiley. 674.

46. Soil Conservation Service, *Land resource regions and Major Land Resource Areas of the United States*. Agriculture Handbook 296. 1981, Washington, DC: US Government Printing Office. 156.

47. Soil Science Society of America, *Glossary of soil science terms*. 1997, Madison, WI: Soil Science Society of America. 134.

48. Soil Survey Division Staff, *Soil survey manual*. United States Department of Agriculture Handbook No. 18. 1993, Washington, DC: US Department of Agriculture. xix, 437.

49. Soil Survey Staff, *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. Agricultural Handbook 436. 1975, Washington, DC: US Department of Agriculture Soil Conservation Service. 754.

50. Soil Survey Staff, *Keys to Soil Taxonomy*. 6th ed. 1994, Washington, DC: US Government Printing Office. iv, 306.

51. Soil Survey Staff, *National Soil Survey Handbook*. Revised December 1997 ed. Title 430-VI. 1997, Washington, DC: US Government Printing Office.

52. Soil Survey Staff, *Keys to Soil Taxonomy*. 8th ed. 1998, Washington, DC: US Government Printing Office.

53. Soil Survey Staff, *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. 2nd ed. Agricultural Handbook 436. 1998, Washington, DC: US Department of Agriculture Soil Conservation Service. 754.

54. Stein, A., M. Hoogerwerf, and J. Bouma, *Use of soil-map delineations to improve (co)kriging of point data.* Geoderma, 1988. **43**(163-177).

55. Steur, G.C.L., W. Paas, and H.d. Bakker, *The soil maps of the German - Netherlands border-area project: a comparison of maps, mapping methods and classification*, in *Perspectives in land evaluation*, J.C.F.M. Haans, Editor. 1984.

56. Sykes, J.B., ed. *The concise Oxford dictionary of current English*. 7th ed. . 1983, Clarendon Press: Oxford, England. xx, 1260.

57. Upchurch, D.R. and W.J. Edmonds, *Statistical procedures for specific objectives*, in *Spatial variability of soils and landforms*, M.J. Mausbach and L.P. Wilding, Editors. 1991, Soil Science Society of America: Madison. p. 49-71.

58. Van Wambeke, A. and T. Forbes, eds. *Guidlines for using Soil Taxonomy in the names of soil map units*. SMSS Technical Monograph No. 10. 198?, Soil Management Support Service: Washington, DC. v, 73.

59. Vink, A.P.A., *Planning of soil surveys in land development*. International Institute for Land Reclamation and Improvement Pub. 10. 1963, Wageningen: Veenman & Zonen.

60. Vink, A.P.A., *Land use in advancing agriculture*. 1975, New York: Springer-Verlag. x, 394 p.

61. Webster, R. and M.A. Oliver, *Statistical methods in soil and land resource survey*. 1990, Oxford: Oxford University Press.

62. Western, S., *Soil survey contracts & quality control*. Mongraphs on Soil Survey. 1978, Oxford: Clarendon Press. 284.

63. Williams, J.R., K.G. Renard, and P.T. Dyke, *EPIC: a new method for assessing erosion's effect on soil productivity.* Journal of Soil and Water Conservation, 1983. **36**: p. 381-383.

64. Zinck, J.A., *Physiography & Soils*. ITC Lecture Notes SOL.41. 1988, Enschede, the Netherlands: ITC.