the ranges in soil characteristics of the official soil series. Use of these series for naming and interpreting map units in second-order soil surveys portrays a degree of precision to users that we have not attained in most instances and can result in credibility problems for soil surveys. We conclude that attempts to make ranges in soil properties in map units correspond to ranges defined for official soil series are pointless because distributions of soil properties do not lend themselves to hierarchical arrangement (Webster, 1968) and small map scales prevent their being mapped. The concepts of similar and dissimilar soils and inclusions are helpful to soil surveyors and correlators, but are not understood by many users since the tabulated interpretations of use and management for the map units in published soil survey reports are reported by the soil series.

It would be better to map whatever is mappable at a given scale and adjust series concepts to correspond to map units or to record the proportion and pattern of occurrence of soils in the map unit by any convenient method as suggested by Beckett and Webster (1971). Fordham and Green (1980) provide an example of listing several principal soil series within their map units as evidence of internal variability. This approach is feasible since second-order soil surveys are not site specific. There are other alternatives that should be explored by research that may provide more useful soils information than research to decide the placement of a typical soil profile or "pedon" in *Soil Taxonomy* selected on the basis of field criteria and allowing the range in soil properties specified for that taxon to determine interpretations for the map unit.

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Application of a Statistical Soil-Landscape Model to an Order III Wildland Soil Survey[1]

H. F. SHOVIC AND C. MONTAGNE[2]

ABSTRACT

Data organization, analysis, and documentation have long been a concern in the soil survey process. Existing computer aided systems are often either not widely available, not "user friendly," or not very applicable to field mapping situations. These concerns are addressed using a simulation approach. A statistical model of the landscape and soils in the survey area is described. The data base used in the soil -landscape model consists of discrete sample points that are randomly distributed (for soil taxa only), mutually exclusive, and independent. The data are representative of other site characteristics. The concepts of statistical estimation, conditional probability, quantified prediction improvement, and selective sorting are applied to use the model in the mapping process. Applications include systematic development of soil-landscape relationships and legends; documented justification for decisions as to data adequacy, soil interpretations, map unit differentia, variability, and taxonomic descriptions; and increasing accuracy of soil correlation. Programs are standard and widely available.

Additional Index Words: **computer applications, simulation, soil mapping.**

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THE MOST IMPORTANT purposes of a soil survey are to show the geographic distribution of soils and other important landscape properties, and to interpret these for specified uses. In the Rocky Mountains, forest uses generally are more varied and less intensive than those on agricultural or urban land. Therefore, soil surveys are often at the Order III level, at scales ranging from 1:24 000 to 1:63 000 and at taxonomic levels above the soil series. Soil-landscape relationships are complex because of large variation in local climates, vegetation, parent materials, and topography. Landform, vegetation, or geologic characteristics are more often used for phase criteria than in detailed surveys. Finally, limited access reduces the efficiency of conventional mapping techniques. Not all map unit boundaries are verified by transecting or traversing. Remote sensing and widely spaced observations with some traversing are used to predict soil and landscape features and for delineation of most map units. The maximum use should be made of all data, since it is

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of limited extent and must represent large areas of the soil and landscape.

Systems simulation is a collection of techniques used to represent complex reality with models. We manipulate and observe the models as they operate to help us learn about reality. They can be analytical (deterministic) or statistical, but are often numerical, complex, and computer based. In the past, the lack of easily accessible computing power has limited modeling efforts in field survey situations. However, computing power is now becoming available to field scientists and uses are increasing.

Computers are now widely used in the soil survey for manuscript preparation, statistical studies of individual soil properties or taxonomic limits, list processing, summaries of interpretations or other properties by taxonomic class, or soil pedon data bases (Soil Survey Staff, 1982). Various computer aided map processing systems have been developed (Giltrap, 1983b; Amidon, 1978; Nelson and Johnson, 1976; Ragg, 1977). Mathematical techniques of classification and mapping have been explored (Giltrap, 1983a, 1981; Webster, 1978). There are numerous data handling systems, e.g., Kosaki et al. (1980), Bie and Schelling (1977), or Haantjens, et al., (1975). Most of the above techniques, though, are either not widely available, not friendly enough for field scientist use, or are too cumbersone for day to day use. The purpose of this paper is to report on the application of computer oriented simulation techniques to the soil mapping process. A statistical model of the soil and landscape is proposed to serve as an interactive, field oriented aid in making maximum use of limited data.

METHODS

The Soil Survey of the Gallatin National Forest Area (SW Montana) was begun in 1975 and field work was completed in 1981 (Davis and Shovic, 1985). The area surveyed is about 600 000 ha, of which about 100 000 ha has road access. The proposed models were developed and tested concurrently with this survey. Precipitation ranges from 50 to 100 cm. Vegetation ranges form grassland through Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*) forests, to alpine tundra. Elevations are from 1800 to over 3600 m. Landforms include steep stream break lands, rolling hills, glaciated lands, and broad, gently rolling plateaus. Geologic materials include igneous intrusions, folded limestones, sandstones, shales, crystalline basement rocks, and volcanic flows.

Soil properties vary widely in response to this variance in soil forming factors. Cryoborolls and Cryochrepts are most common where parent materials are weathered or eroded from rocks of acid composition. Cryoboralfs are associated with more basic rocks. Mode of deposition, age, and weathering regimes often control particle size class. Soils formed in glacial till are often very cobbly, while those formed in outwash are sandy. Soils formed in material weathered from limestone can be calcareous and medium textured, or noncalcareous and moderately fine textured depending on relative age of bedrock exposure. Soils under grassland vegetation generally have mollic epipedons. However, they can also have paleo–argillic horizons that may reflect previous cycles of forest vegetation.

The philosophy of the system involves developing a model that represents soils and their relationships to landscapes. This model of reality is viewed in different ways that are useful to the soil surveyor. The various "views" are generated by programs that manipulate the data in different ways to represent "viewpoints". Each viewpoint depicts reality somewhat differently and is biased toward the objectives of the surveyor.

The model is represented by a data base which represents estimates of the actual occurrence of soils on the landscape. The data base contains a serial listing of summaries of soils, vegetation, parent material, and landform data for sample sites. It is updated as data are gathered during the survey, to advance the model toward a more accurate estimate of "reality".

The soil and site data represent discrete areas or points on the landscape. They are accurately located on maps or on air photos and fit into existing systems for describing and classifying soils, geology, landform, and vegetation. The data are entered serially, each record representing a sample site. There are no restrictions on the types of data collected except that it be tied to a specific sample site. Continuous data is classed, either during data input or during computer runs, since all statistics are based on discrete or "frequency" data. The need to assign all site data to discrete units encourages the scientist to develop significant and important limits for each class to enable the development of discrete map units and interpretations. *Soil Taxonomy* (Soil Survey Staff, 1975) is used for soil classification at the family level. The series level is excluded because of the difficulty of interpreting quantitative limits from series descriptions, the large number of potential classifications, and the lack of established series in the survey area. The data base is designed to be a random sample of soils or soil characteristics. This means there is no concerted effort during sampling to look for a certain soil. Theoretically the only controls on the kinds of soils found on a site are the site features, which predict soil features to a greater or lesser extent depending on their relationships to soil forming factors. Therefore, the site features that control site selection must be representative of the area as a whole. They are not clustered on or biased towards any criterion except on that of the feature's areal extent.

The sample base must be large enough to provide an adequate random sample of the characteristics of interest. The achievable precision of predictions is directly related to the data base size, the variability of soils, and the survey objectives. There were 1594 total sites in the Gallatin data base at the end of the survey process (380 ha per site or 2.6 map unit delineations per observation). Data are entered as the survey progresses and are analyzed during the survey process. Therefore, later predictions are more detailed and/or more reliable than earlier ones.

There are four analytical concepts used in dealing with the model, three statistical and one organizational. The first concept is that the relative frequencies of soil feature occurrence are unbiased estimators of their probabilities. This is valid because the sample sites are randomly distributed, discrete, mutually exclusive, and are assumed to be independent. (Steel and Torrie, 1960), (Miller and Freund, 1965, p. 39, 186– 187).

The second is the concept of conditional probability (Miller and Freund, 1965, p. 25–28). When the symbol P(A) is used for the probability of A, the symbol implies "given some sample space S". For example, if only volcanic terrain is sampled then the probability of finding a given soil type may be different than if the entire survey area is the sample space. This equates to the conditional probability of a soil type given the "volcanic rock" subset of all potential rock types. This is calculated as

$$P(A\ B) = P(A \text{ and } B)/P(B) \qquad [1]$$

where P(A B) is the probability of A given B, P(A and B) is the probability of A and B, and P(B) is the probability of B alone. P(B) cannot be calculated directly using the data base described above because site features such as rock type are not sampled randomly. P(A B) is therefore estimated using a random sample of soils within a subset of the entire sample space, i.e. a given rock type. Cross tabulations of sample site data are used to estimate these probabilities.

The third concept is that of prediction improvement. One of the most important reasons for mapping landscape features is to predict the soils beneath them. Any differentiating feature selected for this reason should improve the prediction of soils. To express this numerically we propose a prediction improvement factor (PIF). It is calculated by comparing the probability of a soil's occurrence when a site feature is used to select the sample site, to the probability of the soil's occurrence without selection of any site feature. It is calculated as:

$$\mathrm{PIF} = \mathrm{P}(\mathrm{A\ B})/\mathrm{P}(\mathrm{A}) \text{ if } \mathrm{P}(\mathrm{A\ B}) \geq \mathrm{P}(\mathrm{A}) \qquad [2]$$

or

$$\mathrm{PIF} = -\mathrm{P}(\mathrm{A})/\mathrm{P}(\mathrm{A\ B}) \text{ if } \mathrm{P}(\mathrm{A\ B}) < \mathrm{P}(\mathrm{A})\,. \qquad [3]$$

where PIF = prediction improvement factor, and P(A) = probability of the occurrence of "A" alone.

The larger the absolute value of the PIF is, the larger the improvement in predictivity is for the soil feature A using that site feature B. If PIF is near 1.0, there is little improvement in prediction over not using the site feature or "predictor variable". If the PIF is positive and large, the prediction of the soil type is improved and the soil is more likely to occur than if no predictors are used. If the PIF is negative but large, prediction is still improved, but the soil type or predicted variable is less likely to occur where that site feature is present than if no predictors are used. Since all PIFs are calculated from random estimates of actual probabilities sample size is important. Accurate interpretations are unlikely with small samples because of random variation. Also, small differences in frequencies may make a disproportionately large difference in the PIF. Of course, if there are too few observations at a given level of generalization, the level can be raised until sufficient.

The fourth concept deals with nonnumerical analysis of information in the data base. The mapping process is by nature probabilistic and the criteria for development of mapping differentia are often complex. Also, the occurrence of individual soils is controlled by many factors that vary in importance in different areas. No individual predictor is sufficient for all soil features. Therefore, the above analytical concepts cannot be used alone without judgement and observation of other data. If data are also organized and displayed in a nonnumerical manner, the soil surveyor can make use of his capacity for synthesis. Soil and site information in the data base is selectively sorted at different levels and displayed in an easily scanned format to make a synthetic analysis and to verify that the numerical analysis is realistic.

A UNIVAC series 1100 mainframe computer was used with a data base management system (SPSS or Statistical Package for the Social Sciences) (Nie, et al., 1975; Hull and Nie, 1979). This set of programs allows great flexibility in output format and data transformations. It has standardized control card formats for all programs, which simplifies data manipulation. Finally, it uses natural language control statements, and variable labeling is extensive and easily understood. Programs used are noted in the figures.

DISCUSSION

The landscape model represents the soil and landscape of the survey area. The surveyors' objective is to differentiate this reality into meaningful areas on the land (map units). To do this, the model is viewed from different viewpoints in the context of the soil survey process. Relevant steps in this process are:

1. Compilation of existing data.
2. Preliminary field studies and initial stratifications.
3. Development of initial mapping legend.
4. Production field mapping including further sampling of soils.
5. Interim correlation and remapping.
6. Iteration of steps 4 and 5 until field mapping is finished, mapping accuracy is adequate, and mapping legend is complete.
7. Final correlation and writeup.

Table 1. Frequencies of soil site data: great group (modified from output of FREQUENCIES program).

Great group	Absolute frequency	Frequency (%)
Cryoboralfs	507	31.8
Eutroboralfs	44	2.8
Glossoboralfs	9	0.6
Cryorthents	14	0.9
Cryochrepts	295	18.5
Cryumbrepts	27	1.6
Ustochrepts	44	2.8
Argiborolls	133	8.3
Cryoborolls	369	23.1
Haploborolls	76	4.8
Other	76	4.8
Total	1594	100.0

In step 2 above, data are collected for sample sites representing groups of apparent soil forming factors. For the Gallatin Forest, data was entered in 80 column records. Codes were used for geology, vegetation groups, and landforms.

In Steps 2 and 3, soil-landscape relationships are developed. Three analytical tools are used. First, frequency tables are generated that show estimates of the relative extent and importance of soils in the survey area, i.e. Great Groups (Table 1). The most extensive great groups that occur in the survey area are Cryoboralfs, Cryochrepts, and Cryoborolls. If these all differ in management implications, they are likely to be the ones that should be analyzed in more depth. Other tables are used to assure adequate representation of different site features.

Second, conditional probabilities and prediction improvement factors (PIFs) are evaluated (Table 2). Since all soil order occurrences are based on a random sample, the probability of any order's occurrence is given by the right hand P column, i.e. 35% for Alfisols. The conditional probabilities of a soil order, given a specific geologic group is known, are in the CP rows. For example, the probability of finding Alfisols, given the geology group crystalline rock is 15%. The PIF for Alfisols using crystalline rock as a predictor is then −35/15 or −2.3. This means that it is 2.3 times less likely to find Alfisols in crystalline rock than if no rock type is known. Similarly, Inceptisols are twice as likely to occur in crystalline rock. The rock type is a good predictor for these two soil orders, but is not for Mollisols (PIF = −1.1).

Since all PIFs are calculated from estimators of actual probabilities, sample size is important. Experience indicates accurate interpretations are unlikely below n = 10 for predicted variable classes and below 50 for predictor variable classes. In Table 2, the classes Histosols, and Obsidian sand are disregarded. Also, since zero cell values may lead to undefined PIFs they

Table 2. Cross-tabulations and prediction improvement factors (PIF) of soil orders with geology groupings (modified from output of CROSSTABS program).

	Geology groups									
Soil order	Crystalline rock	Rhyolite	Other volcanic rock	Shale	Shale: volcanic	Limestone	Sand-stone: soft	Sand-stone: hard	Obsidian sand	Total P
Alfisol										
Count	61	35	158	40	103	48	74	43	0	562
CP‡	15%	49%	45%	49%	43%	29%	43%	36%	0%	35%§
PIF	−2.3	1.4	1.3	1.4	1.2	−1.2	1.2	1.0	†	
Entisol										
Count	10	1	2	4	0 (1)	3	3	4	0	27
CP	3%	1%	1%	5%	0% (0.4%)	2%	2%	3%	0%	2%
PIF	1.5	−2.0	−2.0	2.5	−4.8	1.0	1.0	1.5	†	
Histosol										
Count	1	0	0	0	0	0	0	0	0	1
CP	0.3%	0%	0%	0%	0%	0%	0%	0%	0%	0.3%
PIF	†	†	†	†	†	†	†	†	†	
Inceptisol										
Count	179	30	44	5	11	34	42	27	1	373
CP	45%	42%	13%	6%	5%	20%	24%	22%	100%	23%
PIF	2.0	1.8	−1.8	−3.8	−4.6	−1.2	1.0	1.0	†	
Mollisol										
Count	144	5	141	32	125	83	54	47	0	631
CP	36%	8%	40%	40%	52%	49%	31%	39%	0%	39.7%
PIF	−1.1	−5.0	1.0	1.0	1.3	1.2	−1.3	1.0	†	
Column total	395	71	345	81	239	168	173	121	1	1594
Average PIF	1.7	2.6	1.5	2.2	3.0	1.2	1.1	1.1		

† PIF not calculated; sample size inadequate.

‡ "Conditional" probability of occurrence of soil order given site in specified rock type (CP).

§ Probability of occurrence of soil order, given no other information (P).

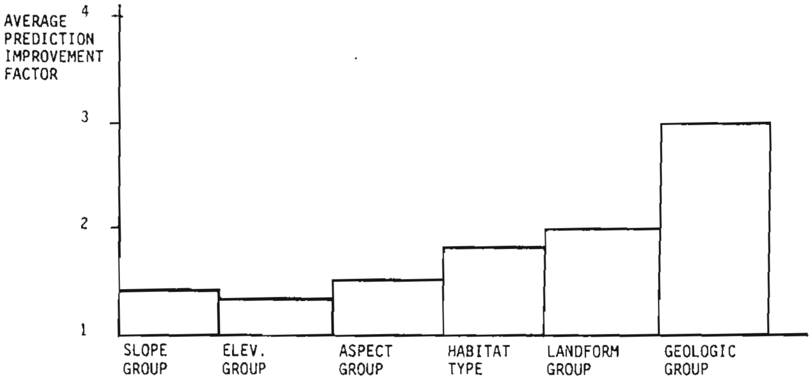

Fig. 1. Average prediction improvement factors for various predictor groups for soil particle size class.

are changed to "1s" for calculation, i.e. for the Entisol — shale-volcanic cell, the value used for the PIF calculations is 1/239, not 0/239.

PIFs are averaged to give an average PIF for the predictors (Table 2). Note that Rhyolite and Volcanic Shale are good predictors of soil orders (2.6 and 3.0 respectively). PIFs are also averaged for predicted variable classes to justify the use of various predictor groups (Fig. 1). Note that geologic group is the best predictor of particle size class. This analysis helps in the selection of certain features as mapping criteria. Interactions between predictors are not evaluated in this level of analysis, but probably are important in multiple factor prediction.

The third tool is selective sorting by tentative mapping criteria. Any sample site data categories can be used for sort keys. The sorts are evaluated by inspection for their quality in predicting soils. Figure 2 depicts part of a sort by landform for sample sites in the geologic group Rhyolite. Note that Cryochrepts are a small part of the soils formed in glacial deposits (glacial depos) but they make up a large part of the soils on ridgetops (frost churn). Cryoboralfs make up a much larger part of the glacier derived soils. Also, the AW/VASC habitat type dominates the ridgetops while AF habitat types occur on glacial deposits. These sorts suggest relationships that can then be tested and applied in mapping to predict soils, in this case Cryochrepts vs. Cryoboralfs. Also, meaningful and consistent phases can be developed, in this case, AW/VASC (noncommercial forest) vs. AF types which are usually commercial forestland.

Sample site data are added to the landscape data base and the appropriate programs are run against it until the surveyor is satisfied relationships are adequately defined. In step 3, the mapping legend is developed using map unit differentia and soil taxa that are important to soil prediction and interpretations. Tools such as Table 1 and 2, and Fig. 1 and 2 are used ot help make these decisions. Laboratory data are also used. In this survey area 77 samples sites were classified in the Unified system (Sowers and Sowers, 1970). Figure 3 depicts some relationships of soil features to this engineering data. For example, the loamy skeletal

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GEOLOGIC         LANDFORM           PHOTO IDEN  MTN    TRNSCT TYPE CLASSIFICATION                    SUR SEC ELE   SLP ASP VT HG HABITAT
GROUP                                           RANGE OR     OF                                      HOR HOR VA                  TYPE
                                                      MAP    STOP                                            TION

RHYOLITE         FROST CHURN


                                    62-155-M6   HBGN  H95    R    TYPIC       CRY  OCHR EPTL-SK  OCH CAM 7200  25 E     1 Q  AFVAGL
                                    62-153-M4   HBGN  H88    R    TYPIC       CRY  OCHR EPTF-L   OCH CAM 7700  45 N     1 Q  AFVASC
                                    62-155-2    HBGN  174    D    MOLLIC      CRY  BOR  ALFL-SK  OCH ARG 6600  22 W     1 U  AWVASC
                                    62-162-A    HILGD H52    R    TYPIC       CRY  BOR  ALFL-SK  OCH ARG 8600   1 FL    1 U  AWVASC
                                    63-139-4    HILGD 83     D    LITHIC      CRY  OCHR EPTL-SK  OCH CAM 8700   5 SE    1 U  AWVASC

                 NO OF ST                     5
                 N OF ELV                                                                            5
                 N OF SLP                                                                                   5
                 ELV MN                                                                              7760
                 SLP MN                                                                                    20
                 MIN                                                                                 6600   1
                 MAX                                                                                 8700  45


                 GLACIAL DEPOS

                                    62-162-9     HILGD 61     D    TYPIC       CRY  BOR  ALFL-SK  OCH ARG 7300   5 N     1 T  AFARCO
                                    63-145-1082  HBGN  154    D    GLOSSIC     CRY  BOR  ALFF-L   OCH ARG 6680   1 FL    1 Q  AFCARU
                                    62-155-M12   HBGN  H101   R    TYPIC       CRY  BOR  ALFF-L   OCH ARG 6720  15 N     1 Q  AFCARU
                                    62-155-M13   HBGN  H102   R    TYPIC       CRY  OCHR EPTL-SK  OCH CAM 6680  10 N     1 Q  AFCARU
                                    62-162-13    HILGD 65     D    GLOSSIC     CRY  BOR  ALFL-SK  OCH ARG 6950  25 N     1 T  AFLIBO
                                    61-206-5     HILGD 39     D    MOLLIC      CRY  BOR  ALFL-SK  OCH ARG 7860  25 E     1 T  AFLIBO
                                    62-162-A87   HILGD H54    R    TYPIC       CRY  BOR  ALFF     OCH ARG 7200  10 W     1 DD AFLIBO
                                    63-145-1081  HBGN  153    D    GLOSSIC     CRY  BOR  ALFL-SK  OCH ARG 6720   9 E     1 Q  AFVASC
                                    63-145-18    HBGN  180 *  D    MOLLIC      CRY  BOR  ALFC-L   OCH ARG 6800  15 E     1 Q  AFVASC
                                    63-145-12    HBGN  156    D    MOLLIC      CRY  BOR  ALFF-L   OCH ARG 6900   9 N     1 Q  AFVASC
                                    61-206-3     HILGD 37     D    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM 8170  12 E     1 Q  AFVASC
                                    62-155-M14   HBGN  H103   R    TYPIC       CRY  BOR  ALFF-L   OCH ARG 6840  10 N     1 N  DFVAGL
                                    62-155-M11   HBGN  H100   R    TYPIC       CRY  BOR  OLLL-SK  MOL CAM 6680   5 FL    4 I  NFMM
```

Fig. 2. Sort of sample site data by geologic group and landform (partial output of SORT CASES/REPORT programs).

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* * * * * * * * * * * * * * * * * * * *   C R O S S T A B U L A T I O N   O F   * * * * * * * * * * * * * * * * * * * *
   UNIFIED                                                     BY  PRTS       PARTICLE SIZE CLASS
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *  PAGE  1 OF  2

                  PRTS
          COUNT  I
        ROW PCT  IS-SK     L-SK      CL-SK    C-L       F-L       F         VF        S            ROW
        COL PCT  I                                                                                TOTAL
        TOT PCT  I       2.I       3.I       4.I       5.I       6.I      10.I      11.I      12.I
UNIFIED  --------I---------I---------I---------I---------I---------I---------I---------I---------I
         CH      I      0  I      0  I      0  I      0  I      0  I      0  I      1  I      0  I      1
                 I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I  100.0  I     .0  I    1.3
                 I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I   33.3  I     .0  I
                 I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I    1.3  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         CL      I      0  I      1  I      0  I      0  I      4  I     10  I      0  I      0  I     15
                 I     .0  I    6.7  I     .0  I     .0  I   26.7  I   66.7  I     .0  I     .0  I   19.5
                 I     .0  I    3.7  I     .0  I     .0  I   25.0  I   62.5  I     .0  I     .0  I
                 I     .0  I    1.3  I     .0  I     .0  I    5.2  I   13.0  I     .0  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         GC      I      0  I      2  I      0  I      0  I      1  I      0  I      0  I      0  I      3
                 I     .0  I   66.7  I     .0  I     .0  I   33.3  I     .0  I     .0  I     .0  I    3.9
                 I     .0  I    7.4  I     .0  I     .0  I    6.3  I     .0  I     .0  I     .0  I
                 I     .0  I    2.6  I     .0  I     .0  I    1.3  I     .0  I     .0  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         GM      I      0  I     19  I      0  I      0  I      3  I      0  I      0  I      0  I     22
                 I     .0  I   86.4  I     .0  I     .0  I   13.6  I     .0  I     .0  I     .0  I   28.6
                 I     .0  I   70.4  I     .0  I     .0  I   18.8  I     .0  I     .0  I     .0  I
                 I     .0  I   24.7  I     .0  I     .0  I    3.9  I     .0  I     .0  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         GW      I      1  I      0  I      0  I      0  I      0  I      0  I      0  I      0  I      1
                 I  100.0  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I    1.3
                 I   20.0  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I
                 I    1.3  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         MH      I      0  I      0  I      0  I      0  I      0  I      3  I      2  I      0  I      5
                 I     .0  I     .0  I     .0  I     .0  I     .0  I   60.0  I   40.0  I     .0  I    6.5
                 I     .0  I     .0  I     .0  I     .0  I     .0  I   18.8  I   66.7  I     .0  I
                 I     .0  I     .0  I     .0  I     .0  I     .0  I    3.9  I    2.6  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
         ML      I      0  I      2  I      1  I      0  I      0  I      1  I      0  I      0  I      4
                 I     .0  I   50.0  I   25.0  I     .0  I     .0  I   25.0  I     .0  I     .0  I    5.2
                 I     .0  I    7.4  I  100.0  I     .0  I     .0  I    6.3  I     .0  I     .0  I
                 I     .0  I    2.6  I    1.3  I     .0  I     .0  I    1.3  I     .0  I     .0  I
                -I---------I---------I---------I---------I---------I---------I---------I---------I
          COLUMN        5        27         1         8        16        16         3         1        77
           TOTAL      6.5      35.1       1.3      10.4      20.8      20.8       3.9       1.3     100.0
```

Fig. 3. Cross tabulation of soil particle size class with unified classifications (partial output of CROSSTABS program) S-SK = sandy–skeletal; L-SK = loamy-skeletal; CL-SK = clayey-skeletal; C-L = coarse-loamy; F-L = fine-loamy; F = fine; VF = very fine; S = sandy.

particle size class tends to have GM soils, while the Fine class has more CL soils. Cross tabulations with these and other soil and site features were examined to determine the best predictors of the C horizons' Unified classifications.

Soil taxonomic units at the family level and above are described by the subset of soil sample sites occurring within their class limits. Figure 4 is a sort by soil family. It is used to select all pedon descriptions occurring within the family limits and to describe the

```
CLASSIFICATION                               MAP     PHOTO IDEN   MTN     TRNSCT  TYPE  SUR   SBC   ELE-     SLOPE  ASPCT  LFRM,  HT GP  HABITAT
                                             UNIT                 RANGE   OR      OF    HOR   HOR   VATION                 GEOL,         TYPE
                                                                          MAP     STOP                                     VTYP

MOLLIC       CRY   BOR  ALFCL-SK

                                             46.2A   70-223-3     CRAZY   61      D     OCH   ARG      6600      5  E      D82    A      AGGR
                                             53.3C   213-131      GALTN   T3-1    R     OCH   ARG      6800     26  N      C31    T      AFLIBO
                                             71.1C   65-154       BRDGR   T2-7    R     OCH   ARG      6600     99         C51           AF
                                             72.2D   218-100      GALTN   T1-1    D     OCH   ARG      7350     15  NW     C31    BB     S SMST
                                             82.2B   62-162-1     HILGD   52      D     OCH   ARG      7920     15  NW     I71    Q      AFVASC

NO OF ST                                                              5
N OF ELV                                                                                                  5
N OF SLP                                                                                                         4
ELV MN                                                                                               7054.0
SLP MN                                                                                                       15.25
MIN                                                                                                    6600      5
MAX                                                                                                    7920     26

MOLLIC       CRY   BOR  ALFF

                                             35.4B   62-155-3     HBGN    165     D     OCH   ARG      7100     20  E      C51    Q      AFVAGL
                                             53.3C   213-131      GALTN   T3-3    R     OCH   ARG      6700      7  S      C31    Q      AFVAGL
                                             54.5C   213-114-5    ABSBR   A105    R     OCH   ARG      6600     50  N      E41    Q      AFVAGL
                                             54.5C   213-114-5A   ABSBR   A105B   R     OCH   ARG      6600     50  N      E41    Q      AFVAGL
                                             71.1A   64-139       BRDGR   T5-1    R     OCH   ARG      7000     15  E      H51    G      AFCACA
                                             71.1A   213-129-27   GALTN   106     D     OCH   ARG      6200     20  W      H61    T      S GATR
                                             72.2A   216-156-8A   GALTN   77      D     OCH   ARG      7100     40  W      H31    T      AFLIBO
                                             72.2D   218-100      GALTN   T1-4    R     OCH   ARG      7640     10  SW     C31    CC     AFVASC
                                             82.2A   213-129-15   GALTN   8    *  D     OCH   ARG      7440      1  FL     I54    I      NFMM
                                             84.1A   64-139-16    BRDGR   90      D     OCH   ARG      6775     10  SE     I51    Q      AFVAGL
                                             84.1A   65-152-2     BRDGR   38      D     OCH   ARG      6500     12  N      I41    Q      AFVAGL
                                             86.2A   213-129-23   GALTN   16   *  D     OCH   ARG      6800     35  SW     I51    S      AFGATR
                                             86.2E   62-159-2     HBGN    201     D     OCH   ARG      8500     10  S      I54    G      NFMM
                                             86.2E   63-139-1C    HILGD   H433    R     OCH   ARG      8320     15  S      I51    DD     DFARCO
                                             86.3B   69-204-13    CRAZY   65      D     OCH   ARG      6880     12  W      I41    Q      AFVACA
                                             87.2A   64-139-20    BRDGR   B200    R     OCH   ARG      7500     50  NE     I52    CC     AFVAGL
                                             87.2D   213-129-29   GALTN   112 *   D     OCH   ARG      6480     30  NE     I51    T      AFLIBO

NO OF ST                                                             17
N OF ELV                                                                                                 17
N OF SLP                                                                                                        17
ELV MN                                                                                               7066.8
SLP MN                                                                                                       22.76
MIN                                                                                                    6200      1
MAX                                                                                                    8500     50
```

Fig. 4. Sort of sample site data by soil family (partial output of SORT CASES/REPORT programs) (CL-SK = clayey-skeletal; F = fine).

associated site features, to estimate extent (by relative frequency) and to write the taxonomic descriptions for the survey area. Finally, it is used to verify that the soil pedons used for taxonomic descriptions are in map unit delineations named for the soils.

Steps 4 through 6 include the physical mapping process and associated analysis. Sample data are taken as delineations are observed on the ground (transects, traverses, or single observations). This information is added to the data base, and is used to verify that mapping criteria and soil landscape relationships are still adequate in new areas. Mapping reliability and quality of map unit concepts are assessed by field inspection and iterative analysis. Viewing data sorted by map unit illustrates this analysis (Fig. 5). The concept of map unit 12-1C is described in the mapping legend as midelevation, gently sloping to rolling ridgetops (LFRM = A) underlain by hard crystalline rocks (GEOL = 1). Soils are predicted to be Typic Cryochrepts, loamy-skeletal (L-SK), mixed, with AF/VASC and AF/VAGL habitat types. Note that the concepts fit well with the field data, though there is some variation. Dystric subgroups occur in some areas but these are similar soils for most purposes. Cryoboralfs and Cryoborolls, though, are dissimilar soils, having higher fertility and water holding capacity. Either these soils are considered limiting inclusions and are described as such, or they are designated as mapping error and corrected.

Soil correlation is "the process of maintaining consistency in naming, classifying, and interpreting kinds of soils and of the units delineated on maps." (Soil Survey Staff, 1982). The mapping legend and maps are modified (in step 5) during mapping to maintain adequate consistency using field checks and outputs such as Fig. 5.

The final field review and final correlation (Step 7) are the official presentation and review of the survey. The tables and figures described above are used to document and demonstrate concepts used in the survey. Figure 5 shows the basic data taken for each map unit, which can be compared to the map unit descriptions. Inclusions can be identified and discussed. Figure 4 is used to show the data used in the taxonomic descriptions. Figure 3 is used to justify interpretive value of soil taxa used in mapping. Any pedon description is easily located for more detailed discussion. Tables 1 and 2, and Fig. 2 are used to justify differentiating criteria. Table 2 and Fig. 1 are used to quantitatively justify the quality of the soil site relationships that were used in developing those criteria. Finally, the tables and figures are used to guide the final narratives on map units, soils, and interpretations.

CONCLUSIONS

We have proposed a statistical model and a system for viewing it that replaces the soil surveyor's memory

```
MAP UNIT                PHOTO IDEN  MTN   TRNSCT TYPE CLASSIFICATION                 SUR SBC ELE-  SLOPE ASPCT LFRM, HT GP HABITAT
                                    RANGE OR     OF                                  HOR HOR VATION             GEOL,      TYPE
                                          MAP    STOP                                                           VTYP

12.1C

                        61-200-H7   HBGN  H128   R    TYPIC       CRY  BOR  ALFC-L   OCH ARG   8000     1 FL    I71  Q     AFVASC
                        213-131-23  GALTN 18     D    TYPIC       CRY  BOR  ALFF-L   OCH ARG   7000    50 N     A11  Q     AFVAGL
                        213-131-26  GALTN 20     D    TYPIC       CRY  BOR  ALFF-L   OCH ARG   6750    20 E     A11  Q     AFCARU
                        218-100     GALTN T2-6   R    TYPIC       CRY  BOR  ALFL-SK  OCH ARG   7500    10 SW    D31  Q     AFVASC
                        218-100     GALTN T2-5   R    TYPIC       CRY  BOR  ALFL-SK  OCH ARG   7500     3 W     D31  Q     AFVASC
                        60-121-7    HILGD 181 *  D    TYPIC       CRY  BOR  ALFL-SK  OCH ARG   7100    35 NE    B11  Q     AFVASC
                        60-121-2    HILGD 5   *  D    MOLLIC      CRY  BOR  ALFC-L   OCH ARG   7400     3       B11  S     AFCACA
                        213-131     GALTN T1-4   R    MOLLIC      CRY  BOR  ALFF-L   OCH ARG   6600     3 W     C11  Q     AFVASC
                        218-100     GALTN T2-4   R    MOLLIC      CRY  BOR  ALFL-SK  OCH ARG   7500    15 W     D31  T     AFLIBO
                        59-126-1    HILGD 1      D    TYPIC       CRY  AQU  EPTF-L   OCH CAM   7700     1 NE    C16  K     DCHD
                        60-123-A11  HILGD H401   R    TYPIC       CRY  AQU  EPTL-SK  OCH CAM   7580     1 FL    B11  S     AFCACA
                        60-123-A7   HILGD H10    R    TYPIC       CRY  OCHR EPTC-L   OCH CAM   7500    38 N     B11  Q     AFVAGL
                        62-153-M4   HBGN  H88    R    TYPIC       CRY  OCHR EPTF-L   OCH CAM   7700    45 N     A21  Q     AFVASC
                        62-155-M6   HBGN  H95    R    TYPIC       CRY  OCHR EPTL-SK  OCH CAM   7200    25 E     A21  Q     AFVAGL
                        62-157-H11  HBGN  H107   D    TYPIC       CRY  OCHR EPTL-SK  OCH CAM   7600     8 SW    A11  Q     AFVASC
                        62-157-H12  HBGN  H108   D    TYPIC       CRY  OCHR EPTL-SK  OCH CAM   7600    12 S     A11  Q     AFCARU
                        62-157-H14  HBGN  H110   D    TYPIC       CRY  OCHR EPTL-SK  OCH CAM   7700    18 SW    A11  Q     AFCARU
                        60-121-4    HILGD 119    D    TYPIC       CRY  OCHR EPTS     OCH CAM   7100    20 NE    B11  Q     AFVASC
                        60-123-A11  HILGD H14    R    TYPIC       CRY  OCHR EPTS     OCH CAM   7580    15 N     B11  S     AFCACA
                        59-126-A3   HILGD H3     R    TYPIC       CRY  OCHR EPTS-SK  OCH CAM   7780     5 S     B11  Q     AFCARU
                        213-131     GALTN T1-1   R    DYSTRIC     CRY  OCHR EPTC-L   OCH CAM   6600    15 NE    A11  Q     AFVAGL
                        214-22-4    GALTN 53     D    DYSTRIC     CRY  OCHR EPTC-L   OCH CAM   7840    30 NW    A11  U     AWVASC
                        213-131     GALTN T1-2   R    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM   6600    20 E     C11  Q     AFVAGL
                        213-131     GALTN T1-3   R    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM   6600    17 N     A11  Q     AFVAGL
                        213-131     GALTN T1-6   R    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM   6600    35 W     A11  Q     AFVAGL
                        213-131     GALTN T1-5   R    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM   6600    20 NE    A11  S     AFCACA
                        60-123-4    HILGD 11     D    DYSTRIC     CRY  OCHR EPTL-SK  OCH CAM   7600    30 NW    B11  Q     AFVASC
                        59-126-2    HILGD 2      D    DYSTRIC     CRY  OCHR EPTS     OCH CAM   7700    10 N     C11  Q     AFVASC
                        60-123-A8   HILGD H11    R    DYSTRIC     CRY  OCHR EPTS-SK  OCH CAM   7950    26 SE    B11  Q     AFVASC
                        61-200-16   HBGN  195    D    ENTIC       CRY  UMBR EPTS-SK  UMB CAM   8000    15 NE    A11  Q     AFVAGL
                        63-141-1    HILGD 89     R    TYPIC       CRY  UMBR EPTL-SK  UBR CAM   8720    15 W     A11  U     AWVASC
                        63-141-8    HILGD H428   R    TYPIC       CRY  UMBR EPTL-SK  UMB CAM   8500    10 N     B11  U     AWVASC
                        214-22-8A   GALTN 57     D    TYPIC       CRY  UMBR EPTS     UMB CAM   7600    45 N     F11  Q     AFVAGL
                        59-126-A2   HILGD H2     R    TYPIC       CRY  AQU  OLLL-SK  MOL CAM   7480    18 E     B11  Q     AFVASC
                        62-157-H15  HBGN  H111   R    ARPC        CRY  BOR  OLLL-SK  MOL ARG   8600    22 S     A11  Q     AFCARU
                        218-100     GALTN T2-1   R    ARGIC       CRY  BOR  OLLF-L   MOL ARG   7500    15 NW    C31  T     AFLIBO
                        218-100     GALTN T2-2   R    ARGIC       CRY  BOR  OLLF-L   MOL ARG   7500    15 NW    C31  T     AFLIBO
                        218-100     GALTN T2-3   R    ARGIC       CRY  BOR  OLLL-SK  MOL ARG   7500    65 S     C31  Q     AFCAGE
                        60-123-1    HILGD 8      D    TYPIC       CRY  BOR  OLLS     MOL CAM   7440    10 E     B11  Q     AFVASC

NO OF ST                             39
N OF ELV                                                                                         39
N OF SLP                                                                                               39
ELV MN                                                                                       7469.7
SLP MN                                                                                              19.64
MIN                                                                                            6600     1
MAX                                                                                            8720    65
```

Fig. 5. Sort of sample site data by map unit (12-1C illustrated here) (partial output of SORT CASES/ REPORT programs).

as the central location for site data and its analysis. We have shown via examples, applications of the system in the soil survey process. We emphasize that it does not replace the surveyors' judgement and experience in analysis of the landscape, map unit design, or correlation. It enhances the process by using the computer models to visualize, recognize, and document relationships that might otherwise be obscured or lost, to more fully utilize soil site data, and to perform tracking functions that would otherwise consume a large part of the survey staff's time and resources. With all the basic documentation for the survey being organized and readily available after the survey is completed, revisions or evaluations are easily accomplished. The information can aid in soil correlation and interpretation when an old survey is to be updated and can provide initial data for future adjacent surveys.

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DIVISION S-6—SOIL AND WATER MANAGEMENT AND CONSERVATION

Tillage Effects on Soil Thermal Properties[1]

K. N. POTTER, R. M. CRUSE, AND R. HORTON[2]

ABSTRACT

Theoretical considerations indicate soil thermal properties may be altered by tillage, but few field studies have been conducted to compare soil thermal properties as affected by conservation or no-till management systems. Surface-soil thermal properties were determined in the row zone for three soils in three tillage systems: conventional till, chisel plow, and no-till. The apparent thermal diffusivity was determined by harmonic analysis of soil temperature data, volumetric heat capacity from the volume fraction of the soil components, and thermal conductivity by the line source heat-probe method. Soil volumetric heat capacity was similar for all tillage treatments. Thermal diffusivity was significantly greater in the no-till system than in conventional and chisel plow tillage systems, indicating that thermal conductivity also was greater in the no-till system. Direct determination of thermal conductivity by the line source heat-probe method at one site indicated that thermal conductivity was more than 20% greater in no-till than in the conventional till system. Percentage surface residue cover had a greater influence on soil temperature and soil heat flux than soil thermal properties.

Additional Index Words: **harmonic analysis, soil heat flux, soil heat transfer, thermal conductivity, thermal diffusivity.**

Potter, K.N., R.M. Cruse, and R. Horton. 1985. Tillage effects on soil thermal properties. Soil Sci. Soc. Am. J. 49:968–973.

TILLAGE INFLUENCES soil temperature by altering soil thermal properties, the surface configuration, and percentage surface residue cover. There have been many experiments concerning surface residue and surface configuration effects on soil temperature. For a review, see Willis and Amemiya (1973) and Voorhees et al. (1981). The general consensus is that spring soil temperatures are reduced with increasing amounts of surface residue. There is evidence, however, that the use of ridge planting may reduce differences in soil temperature between tillage systems while maintaining surface residue cover (Radke, 1982).

The increasing interest in computer modeling of tillage effects on soil temperature makes knowledge of soil thermal properties important (Cruse et al., 1982). Van Duin (1956) discussed the theoretical implications of tillage on soil thermal properties. Decreasing soil porosity or increasing soil water content increased thermal conductivity (λ). Soil heat flux was reduced by loosening the surface soil layer.

Tillage effects on soil thermal properties have been considered in only a few field studies. Thermal diffusivity (α) was larger in a direct-drilled barley field as compared with a plowed field throughout the growing season in England (Hay et al., 1978). The difference in α was attributed to the greater soil bulk density in the direct-drilled field. Allmaras et al. (1977) found λ increased with increasing amounts of secondary tillage following plowing.

With the wide variety of tillage systems available, it is important to understand the effect of tillage on physical properties and processes occurring in the soil. The objective of this study was to determine the effect of widely used tillage systems on soil thermal properties for a variety of soils. Soil heat flux also was determined to compare the effects of ridged and flat no-till systems with other tillage systems.

THEORETICAL BACKGROUND

The method of determining λ, α, and soil heat flux used in this study is based upon solutions to the heat conduction equation. A brief review of the concepts involved is presented.

An equation describing one-dimensional heat transfer in a homogeneous media is:

$$\partial C_v\ T/\partial t = \partial(\lambda\ \partial T/\partial z)/\partial z \qquad [1]$$

where T is the temperature, t is the time, z the depth, C_v the volumetric heat capacity, and λ the apparent thermal conductivity. Assuming that C_v and λ are independent of depth and time, Eq. [1] may be rewritten as:

$$\partial T/\partial t = \alpha\ \partial^2 T/\partial z^2 \qquad [2]$$

where α is the apparent thermal diffusivity ($\alpha = \lambda/C_v$).

With boundary conditions

$$T(o,t) = \overline{T} + \sum_{n=1}^{m} A_{on}\sin\,(n\omega t + \phi_{on}) \qquad [3]$$

and

$$\lim_{z\to\infty} T(z,t) = \overline{T} \qquad [4]$$

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