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SURVEY OF SOIL MAP UNIT SENSITIVITY TO ACID DEPOSITION IN THE SIERRA NEVADA, CALIFORNIA

Prepared For:

CALIFORNIA AIR RESOURCES BOARD
Under Contract No.
A732-037

Prepared By:

NORTH STATE RESOURCES, Inc.
Redding, California

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In Association With

University of California, Davis
Deparment of Land, Air, and Water Resources

Robert Zasoski, Ph.D.

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ABSTRACT

A method for classifying soil map units on the basis of relative response to acid deposition is described. Study area boundaries are the crest of the Sierra Nevada west to the interface of the mesic and frigid soil temperature regimes; and from 35°45'00" north latitude to 39°31'44" north latitude. The Emerald Lake Integrated Watershed Study Area and seventy-eight sampled Sierran lakes are included in the 2,116,448 acre study area.

A computer program was developed which calculates changes in soil base saturation and pH given soil chemical parameters and an acidification regime. A rate of 0.3 kmol H^+/hectare/year was imposed on soils for 50 years to determine relative capacities to maintain base saturation and pH.

One hundred sixty-seven soil samples from forty-three modal soil profiles were analyzed for relevant chemical characteristics. Extrapolations were made on the basis of soil taxonomic similarities to represent the chemical composition of the one hundred fifty taxonomic components which occur in the study area.

Soil chemical data and map unit data were organized in a relational database. Taxonomic units were ranked according to the projected base saturation after fifty years of deposition. This ranking was combined with soil hydrologic grouping and map unit slope to rank soil map units in terms of their relative abilities to attenuate additions of strong mineral acids. Map units on less steep slopes containing high percentages of soils with low runoff characteristics and high buffering capacities are termed least sensitive. Other soils are termed moderately sensitive or most sensitive.

The distribution and relative sensitivities of soil map units are presented in a 1:62,500 scale map registered to USGS 15-minute quadrangles. Forty-five 18-inch by 24-inch sheets are required for coverage of the entire study area.

Approximately 25 percent of the study area (527,564 acres) are least sensitive on the basis of the present ranking criteria. Eighteen percent, (380,677 acres) are moderately sensitive; fifty-six percent (1,183,601 acres) are most sensitive. Water bodies occupy 24,586 acres, or 1 percent of the study area.

Soil map unit delineation boundaries are retained on the sensitivity map. Because of this, in addition to its value as an index to relative map unit sensitivity, the document is a source of regional baseline soil survey information.

ACKNOWLEDGEMENTS

The authors acknowledge the contributions made by the following individuals and agencies, without which this project would not have been possible. Dr. W.J. Walker contributed greatly to development of the computer program which calculated acidification response and provided valuable comments on data analysis. Mr. J-B Chung was responsible for analysis of soil samples at UC Davis and provided excellent data for use in the study. Mr. Daniel Ernstrom of the USDA - Soil Conservation Service assisted in soil correlation and facilitated data transfer from SCS to NORTH STATE RESOURCES. The soil scientists for each of the five national forests included in the study area provided original maps for digitizing, which greatly enhanced the accuracy of the sensitivity map. Special acknowledgement is due the many individual field soil scientists who, over the years, have assembled the soil survey database which is the foundation of the map.

We thank the staff of VESTRA Resources, Inc. for their professional commitment in producing the high quality digitized map. Thanks also to the National Park Service staff, especially Jan van Wagtendonk of Yosemite National Park, and David Graber and Dave Parsons of Sequoia National Park for logistical support. We thank Dr. Gordon Huntington of the University of California at Davis for sharing with us soil survey and soil chemical data for Sequoia National Park.

NORTH STATE RESOURCES' soil scientists Dennis Worrel, Russell Almaraz, and Sanderson Page completed field mapping. Laura Kuh assisted in the technical review; Shirley Park typed the report.

The authors extend special thanks to the California Air Resources Board, especially Dr. Kathy Tonnessen, for their patient support of this effort.

EXECUTIVE SUMMARY

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EXECUTIVE SUMMARY

BACKGROUND

An important statutory goal of the Air Resources Board is to determine where acid deposition is occurring or might be expected to occur in amounts which could be adverse to the environment. The Air Resources Board has funded a number of projects through the Integrated Watershed Study (IWS) at Emerald Lake, Sequoia National Park, to determine the impacts of terrestrial and aquatic acidification on high elevation montane ecosystems. Future research will attempt to place the results of the IWS in a regional context. Soil bodies are suitable for grouping ecological systems with respect to their response to acid deposition and therefore, may be used to extend the IWS findings to wide geographic areas.

This project has two objectives. The first objective is to use taxonomic soil survey information to rank soil bodies in terms of physical and chemical characteristics which may influence watershed response to acid deposition. The second objective is to create a map of soil bodies which shows their geographic distribution and relative sensitivity, and also provides base-line information to compare soils characteristics in different watersheds.

APPROACH

The study area encompasses the frigid and cooler, cryic soil temperature regimes of the western slope of the Sierra Nevada. The northern boundary is the middle fork of the Yuba River; the southern boundary occurs within the Sequoia National Forest. Sensitivity rankings are limited to areas that have been taxonomically surveyed or that were surveyed as part of this project: sensitivity rankings are provided for approximately 2,116,448 acres.

A computer program was developed to simulate changes in soil chemistry induced by acid deposition. Soil samples collected from throughout the study area were used to calibrate the model and as model input. Individual soils were ranked according to their simulated response to acidification with 0.3 kmols H^+/ha/yr over 50 years. In addition to the response ranking of individual soil types, slope and hydrologic soil group (an index of runoff potential), were used to rank the sensitivity response of aggregations of individual soil types (e.g., soil map units). In this study, map unit sensitivity is defined as the relative capacity of study area soil map units to attenuate acid inputs.

Soil map unit boundaries were digitized from published reports. The map was plotted at 1:62,500 scale. Map unit delineations were hatched to indicate the sensitivity class ranking. The map is registered to identical scale USGS 15-minute quadrangles; portions of forty-five 18-inch x 24-inch sheets are required for coverage of the entire study area. The soil survey report for areas within the national parks mapped under this effort, and the database describing soil characteristics in the study area, are submitted as Appendixes A and B, respectively.

RESULTS AND CONCLUSIONS

Approximately 527,564 acres, or 24.9 percent of the study area, are considered least sensitive. Eighteen percent of the area, approximately 380,677 acres, are moderately sensitive. Almost 56 percent of the study area, or 1,183,601 acres, are most sensitive. Water occupies 24,586 acres, or approximately 1.2 percent of the study area.

Typically the least sensitive soil map units contain non-sensitive soils more than forty inches deep. Least sensitive soil map units are level or gently sloping landscapes and include little rock outcrop or other miscellaneous land types.

4) The graphics element of this project should be linked to the database element to create a true geographic information system, (GIS). The GIS could then be used by other researchers to compare environmental characteristics and to simulate the ecological response to acid deposition over large areas.

5) Additional soil samples, presently archived, should be analyzed. The chemical data should be used to refine the sensitivity model and to improve the integrity of the baseline data.

6) An effort should be made to quantify the importance of the litter layer and the effect of fire in determining sensitivity.

7) Soil survey data is widely used in wildland resource management. The Air Resources Board should establish cooperative agreements with land management agencies to share the cost of assembling soil survey information in a consistent format throughout the forested portions of California.

DISCLAIMER

"The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products."

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SUMMARY AND CONCLUSIONS

BACKGROUND

An important statutory goal of the Air Resources Board is to determine where acid deposition is occurring or might be expected to occur in amounts which could be adverse to the environment. The Air Resources Board has funded a number of projects through the Integrated Watershed Study (IWS) at Emerald Lake, Sequoia National Park, to determine the impacts of terrestrial and aquatic acidification on high elevation montane ecosystems. Future research will attempt to place the results of the IWS in a regional context. Soil bodies are suitable for grouping ecological systems with respect to their response to acid deposition and, therefore, may be used to extend the IWS findings to wide geographic areas.

This project has two objectives. The first objective is to use taxonomic soil survey information to rank soil bodies in terms of physical and chemical characteristics which may influence watershed response to acid deposition. The second objective is to create a map of soil bodies which shows their geographic distribution and their relative capacities to attenuate acid inputs. The study also provides baseline information to compare soils characteristics in different watersheds.

APPROACH

The study area encompasses the frigid and cooler, cryic soil temperature regimes of the western slope of the Sierra Nevada. The northern boundary is the middle fork of the Yuba River; the southern boundary occurs within the Sequoia National Forest. Response rankings are limited to areas that have been taxonomically surveyed or that were surveyed as part of this project; rankings are provided for approximately 2,116,448 acres.

A computer program, based on published existing models of soil buffering and response to acid inputs, was developed to calculate relative changes in base saturation and pH for the soils in the study area. The computer program was based on soil exchange reactions and aluminum solubility coupled with solution parameters. The exchange equilibria was fitted to a range of soils collected from throughout the study area and then applied to the remaining soils. Individual soils were ranked according to their calculated response to 50 years of acidification at 0.3 kmol H^+/ha/yr. Response to added sulfuric and nitric acid was measured directly in a number of soils.

Slope and hydrologic soil group (an index of runoff potential) were considered along with base saturation and pH response to rank aggregations of individual soil types, the soil map units, by their relative capacities to attenuate acid inputs. Map units with relatively small attenuation capacity and relatively high runoff potential are termed "most sensitive." Units with relatively large attenuation capacity and relatively low runoff potential are termed "least sensitive." Map units with intermediate characteristics are termed "moderately sensitive."

Soil map unit boundaries were digitized from published reports. The map was plotted at 1:62,500 scale. Map unit delineations were hatched to indicate the sensitivity class ranking. The map is registered to identical scale USGS 15-minute quadrangles; portions of forty-five 18-inch x 24-inch sheets are required for coverage of the entire study area. The soil survey report for areas within the national parks mapped under this effort, and the database describing soil characteristics in the study area are submitted as Appendices A and B, respectively.

RESULTS AND CONCLUSIONS

This study ranks survey area map units in terms of their relative capacities to attenuate acid inputs. Soil map units with small capacities relative to other survey area map units are termed "most sensitive." Map units with greater capacities are termed "moderately

sensitive" or "most sensitive." Quantification of the ecosystem response to acid deposition is beyond the scope of this study due to the complexity and variability of the process involved throughout the approximate 2-million-acre study area.

Approximately 527,564 acres, or 24.9 percent of the study area, is considered least sensitive relative to the remaining 75.1 percent of the study area. Eighteen percent of the area, approximately 380,677 acres, is moderately sensitive. Almost 56 percent of the study area, or 1,183,601 acres, is most sensitive. Water occupies 24,586 acres, or approximately 1.2 percent of the study area.

Typically the least sensitive soil map units contain non-sensitive soils more than 40 inches deep. Least sensitive soil map units are level or gently sloping landscapes and include little rock outcrop or other miscellaneous land types.

Moderately sensitive soil map units contain shallow, non-sensitive soils on steep slopes and sensitive soils on slopes less than 35 percent. Highly sensitive soil map units contain sensitive soils on slopes steeper than 30 percent. Also, map units that contain 50 percent miscellaneous land type are considered highly sensitive, regardless of other characteristics.

Effective soil depth is an important determinant of soil sensitivity within the study area. Initial base saturation, pH, parent material, cation exchange capacity, and organic carbon content were somewhat less influential. The relative importance of soil characteristics in determining sensitivity varied according to soil horizon.

RECOMMENDATIONS

1. The soil survey (i.e., map sheets and database tables) should be used as a tool for comparing soil characteristics of watersheds throughout the 2-million-acre study area. Understanding watershed similarities and differences will assist the ARB in selecting representative locations for future study and monitoring of a variety of environmental characteristics in addition to soils.

2. Soil survey information should be used to:
   - Refine the USGS watershed model;
   - Refine regional lake acidification models; and,
   - Develop, calibrate and test a mechanistic watershed model.

3. Soil survey information should be used as baseline data to monitor changes in edaphic factors in forested areas of California.

4. The graphics element of this project should be linked to the database element to create a true geographic information system (GIS). The GIS could then be used by other researchers to compare environmental characteristics and to simulate the ecological response to acid deposition over large areas.

5. Additional soil samples, presently archived, should be analyzed. The chemical data should be used to refine the sensitivity model and to improve the integrity of the baseline data.

6. An effort should be made to quantify the importance of forest litter layers and the effects of fire and other management practices on soil response to acid inputs.

7. Soil survey data are widely used in wildland resource management. The Air Resources Board should establish cooperative agreements with land management agencies to share the cost of assembling soil survey information in a consistent format throughout the forested portions of California.

INTRODUCTION

Monitoring by the California Air Resources Board (ARB) demonstrates that acid deposition occurs in various regions of California (California Air Resources Board, 1986; Blanchard, et al., 1989). Both wet and dry deposition occur. Information describing wet deposition is more complete than information describing dry deposition. In general, rates of deposition recorded in California are less than deposition rates recorded in the northeastern United States and in western Europe.

Atmospheric acid deposition is a naturally occuring process. Deposition rates measured in the frigid and cryic soil temperature regimes of the Sierra Nevada represent an addition to natural acidifying processes. Forest ecosystems and montane lakes can be sensitive to changes in soil and water chemistry caused by increased atmospheric inputs of strong mineral acids (Schofield, 1976; Ulrich, et al., 1980).

At present, the growth and rigor of California forests appear unaffected by acid deposition (Peterson, et al., 1989). Although recent research suggests reserves of acid neutralizing capacity are small or absent in some Sierran watersheds (Sickman and Melack, 1989; Brinkley and Richter, 1987), evidence linking the acidification of California montane lakes to atmospheric deposition is weak. Time lags are involved in the response of ecological systems to acidic inputs (U.S. Environmental Protection Agency, 1985), and portions of California may differ in their response to acid deposition because of differences in surface water chemistry, geology, and soil type (National Acid Precipitation Assessment Program (NAPAP), 1982). The extent of ecosystems that respond to increased acid deposition and the significance of the relative responses of individual watersheds are not well understood, yet these are important issues that have obvious implications for public policy decisions.

No definition of sensitivity to acid deposition is generally accepted for all situations. Sensitivity may be defined differently for aquatic systems compared to forest ecosystems.

In this study, soil map unit sensitivity is defined on a relative basis. The relative ranking is based on calculated soil response to acid input, soil properties that influence runoff and retention time, and slope. The scope of this study is limited to development of a relative ranking of map unit response to deposition.

The California Air Resources Board has sponsored research to determine the degree and mechanisms by which acid deposition affects natural ecosystems. The ARB has funded a number of projects through the Integrated Watershed Study (IWS) at Emerald Lake, Sequoia National Park, to determine the impacts of terrestrial and aquatic acidification on biological resources. Future research will attempt to place the results of the IWS in a regional context.

A first step in the extrapolation of the IWS studies to the regional level is the adoption of a basis for comparing geographically separate watersheds with respect to their response to acid deposition. Soil bodies are suitable for grouping ecological systems with respect to their sensitivity response to acid deposition for a number of reasons. As the medium for plant growth, soils influence other elements of the biota. The soil mantle acts as a buffer (van Breeman and Wielemaker, 1974; Reuss and Johnson, 1986; Ulrich, 1980). Soil and surficial geologic deposits influence watershed hydrologic characteristics. Finally, a soil taxonomy has been established to consistently group soils based on the degree to which the environmental factors which control soil formation (e.g., climate, biota, relief, geologic parent material, and time) are expressed as soil physical and chemical properties (U.S. Department of Agriculture, 1975).

PROJECT OBJECTIVES

The first objective of this project is to combine an understanding of the mechanisms of soil acidification with taxonomic soil survey information to rank soil bodies in terms of physical and chemical characteristics which may influence watershed response to acid deposition.

The second objective of this study is to create a map of soil bodies which shows their geographic distribution and relative sensitivity to acid deposition according to the criteria developed.

Sensitivity is defined here as the capacity of a soil body to attenuate acid deposition relative to other soil bodies in the study area. "Soil body" is synonymous with the more technical term "soil map unit." Soil map units are selected as the basis for comparison because they are defined in terms of soil and landscape features which influence the effects of acid deposition on other ecosystem components. Soil response was based on the calculated base saturation that would follow a substantial acid input. Assumed inputs were large in order to emphasize differences in soil buffering capacities. The calculated base saturation was adjusted for soil depth and coarse fragment content. Hydrologic soil group, map unit composition, and map unit slope were considered in assigning a relative sensitivity ranking to each unit.

The sensitivity map produced under this effort serves the objectives of the Kapiloff Act and the Air Resources Board in a number of ways. First, it identifies areas where acid deposition may impact terrestrial and aquatic systems at a relatively detailed level of resolution. Second, it provides a basis for extrapolating the results of related research to larger geographic areas. Third, chemical and physical characteristics measured during this study may be used as baseline data by the ARB as it continues to monitor the effects of acid deposition on terrestrial ecosystems. Finally, the soil and landscape information provided by this study can be used as criteria for selecting locations for future ARB efforts to predict the response of forest and aquatic ecosystems to acid deposition.

STUDY AREA BOUNDARIES

A map of the study area is presented in the Index to Map Sheets included in the map envelope. Sensitivity rankings are limited to areas that have been taxonomically surveyed

or that were surveyed as part of this project; sensitivity rankings are provided for approximately 2,116,448 acres of the approximately 3-million-acre high-elevation west slope Sierra Nevada.

The western boundary is defined in terms of taxonomic soil temperature regimes. The boundary is drawn at the interface between the warmer, mesic regime (downslope, outside) and the cooler, frigid regime (upslope, inside). The cryic regime is included upslope to the crest. The elevation of the mesic-frigid boundary moves downslope with increasing latitude. Accordingly, the western survey boundary occurs at approximately 7,000 feet elevation in the southern Sierra and moves downslope to approximately 5,400 feet in the northern Sierra.

The west slope was selected for study because lakes in Sequoia National Park are thought to be more at risk to acidification than eastern Sierran lakes (Sickman and Melak, 1989), and forest resources are most extensive on the west slope. In addition, previous studies have tended to focus on the west slope. The eastern boundary of the study area is the crest of the Sierra Nevada.

Research indicates that coarse-textured soils derived from intrusive igneous parent materials in cool weathering regimes are among the most sensitive to acid deposition. The northern and southern boundaries of the study area are defined primarily on the basis of geologic characteristics. In order to enhance the usefulness of the existing soil resource database, which is arranged by State soil survey areas, some consideration is given to political demarcations.

The northern boundary is the Middle Fork of the Yuba River, which is north of the main body of the Sierran batholith. The northmost extension of the study area is at approximately 39°31'44" north latitude. The southern limit of the study area is the mesic-frigid interface within the boundary of the Sequoia National Forest, or the forest

boundary. The southernmost extension of the study area is at approximately 35°45'00" north latitude.

The study area includes the surveyed, frigid, and cooler cryic soils which occur in the main body of the western slope of the Sierran granitic batholith. Portions of eight state soil survey areas are included. These are the Tahoe, El Dorado, Stanislaus, Sierra, and Sequoia National Forests areas, and the Yosemite, Kings Canyon, and Sequoia National Parks areas. The acreage included within each survey is listed in Table 1.

TABLE 1

STUDY AREA ACREAGE BY STATE SOIL SURVEY AREA

State Soil Survey Area No.	State Soil Survey Area Name	Acreage Included
719	Tahoe National Forest	257,257
724	El Dorado National Forest	334,303
731	Stanislaus National Forest	512,648
750	Sierra National Forest	439,368
760	Sequoia National Forest	454,552
790	Yosemite National Park	43,249
791	Kings Canyon National Park	23,791
792	Sequoia National Park	51,280
	TOTAL	2,116,448

The Emerald Lake Integrated Watershed Study Area and thirty-seven of the lakes sampled in the US-EPA Western Lake Survey Dataset are in the study area. Twenty-one of the lakes studied by Melack, et al. (1985), and twenty of the lakes sampled by the California Department of Fish and Game (McCleneghan, et al., 1985) are also included.

PROJECT RATIONALE

Acid deposition enters the soil via a number of processes and pathways. Deposition is a mixture of acids and salts, with H^+ being an important cation (Reuss and Johnson, 1986), although ammonium input can also be important in some areas (van Breeman, et al., 1982). McFee (1980) listed four parameters which are important to the estimates of soil sensitivity to acid precipitation. These are:

1. Total buffering capacity or cation exchange capacity, provided primarily by clay and soil organic matter.

2. Base saturation of the exchange complex, which related to soil pH.

3. Management systems imposed on the soil, such as liming or other additions.

4. The presence or absence of carbonates in the soil profile.

Most soils act as buffers that resist acidification, although this effect is much diminished in cool, forested regions where a net leaching regime tends to remove cations from exchange sites on clays, organic matter, and oxides, and replaces them with hydrogen ions. The pool of exchangeable cations is limited by the composition of the soil parent material and by weathering rates, whereas the supply of hydrogen is relatively vast so, over time, natural and anthropogenic acidification can occur.

Important soil buffering reactions in forest ecosystems include cation exchange, mineral weathering, organic matter decomposition and microbial respiration, elemental cycling, aluminum precipitation and dissolution, and sulfate adsorption (Binkley and Richter, 1987; van Breeman and Wielemaker, 1974; Ulrich, 1980). If forest soils buffering is dominated by cation exchange processes, mineral weathering, anion adsorption and aluminum reactions (van Breeman and Wielemaker, 1974), because carbonates are normally absent.

A previous effort to classify Sierran soils with respect to their response to acidic deposition found cation exchange capacity, base saturation, and soil pH to be important variables. Those having a lesser influence were soil organic matter, soil depth, and parent material (Wyels, 1986). Weintraube (1986) examined the response of Sierran watersheds to acid inputs and concluded that Eastern Brook Lakes and Emerald Lake watersheds were extremely sensitive to acidification because of the low weathering rates and thin surfacial cover. McColl (1981) developed a model to assess the sensitivity of Sierran soils. In his model cation exchange and the sum of exchangeable bases were important components in assessing sensitivity. He concluded that poorly developed, shallow granitic soils at higher elevations and soils with low exchangeable bases were the most sensitive of those he investigated. The sum of exchangeable bases was the most predictive soil parameter in the model of soil sensitivity developed by McColl. He applied limits of 5 to 15 meq of exchangeable bases to divide the most, moderate, and least sensitive soil groups.

A computer can be used to calculate changes in soil base saturation and pH resulting from acid input. Evaluation of the response of soil map units to acid inputs requires consideration of soil physical properties and environmental factors in addition to soil chemical properties. Taxonomic soil survey information, supplemented by additional chemical analyses, provides baseline soil characterizations which can be used as bases to calculate soil acidification. Soil survey information and the results of the acidification

calculations can be used to rank soil bodies in terms of their relative response to acid deposition.

CONCEPTUAL BASIS FOR ESTIMATING pH AND BASE SATURATION CHANGES IN SIERRAN SOILS

Sierran soils receive wet acidic deposition in two ways. One is through snow pack melt each spring, and the other is through sporadic summer and early fall rain events. Thus, Sierran soils are subject to pulses of acidification (Lund, et al., 1989). This being the case, it can be argued that rapid reactions between added acidity and the exchange complex are important buffering components in Sierran soils since these reactions are rapid enough to react with water as it flows through the soil. Such a reaction sequence can be simulated by an equilibrium reaction since the rate of reaction is faster than the water flow rate in the system. Therefore, an equilibrium model was chosen to simulate the response of Sierran soils to acid inputs.

SOIL CHEMISTRY RELATIONSHIPS INCLUDED IN THE COMPUTER PROGRAM

The following reactions are considered important in determining soil solution composition and in determining how that composition might be altered by acidic inputs suggested in the conceptual framework outlined above. For clarity, the reactions are presented as 'solid phase' and 'solution phase' reactions. Following each reaction is a brief description of its role in soil acidification and the input data necessary to quantify the reaction.

Solid Phase and Cation Exchange Reactions

1. Interlayer aluminum hydroxide or microcrystalline gibbsite solubility.

$$Al(OH)_3 + 3\ H^+ \text{ --- } Al^{3+} + 3\ H_2O \quad \text{Log K} = 8.03\text{-}9.00$$

$$A1^{3+} + 3\ OH^- \text{ -------- } A1(OH)_3$$

This reaction may control aluminum solubility in acidic soils. As suggested by the expression, decreasing the pH will dissolve the solid and release aluminum ion to soil solution. Aluminum solution and dissolution may account for a substantial amount of pH buffering in acid soils. Control of solution aluminum by this solubility expression can be tested with ion activity products derived from the soil solution extracts and pH.

2. Exchangeable Aluminum.

$$-\mathrm{Log}(Al^{3+}) = B(pH) + C$$

Where:

B is the slope = 1.05 x (bound aluminum ratio) + 0.345

C is the intercept = -(5.47 x bound aluminum ratio) + 3.879

This empirical relationship was developed by Cronan, et al. (1986) and relates solution aluminum to the amount of aluminum bound to the surface, or the bound aluminum ratio. The bound aluminum ratio is related to base saturation by the relationship: 1 minus bound aluminum ratio = base saturation (sum of Ca+Mg+K+Na ÷ total exchange capacity). Input data necessary to utilize this expression include exchangeable aluminum, sum of exchangeable bases, and pH.

Solution Phase Reactions

1. Aluminum Hydrolysis.

$$Al^{3+} + H_2O = Al(OH)^{2+} + H^+ \quad K=10^{-5.02}$$

$$Al^{3+} + 2H_2O = Al(OH)_2^+ + 2H^+ \quad K=10^{-9.30}$$

As indicated by the reactions, soluble aluminum can significantly influence solution pH by hydrolysis. Soluble aluminum is determined from pH and either exchangeable or mineral soluble aluminum, and the degree of hydrolysis determined from these equations.

2. Carbonate Equilibria.

$$CO_2 + H_2O = H_2CO_3$$

$$H_2CO_3 = H^+ + HCO_3^-$$

$$HCO_3^- = H^+ + CO_3^-$$

These reactions influence the sensitivity of soils to acidic input due to changes in production of alkalinity. In this study the computations are based on estimates of partial pressure of carbon dioxide in the soil atmosphere as well as charge balance considerations useful for estimating alkalinity in natural waters. These data are derived from soil solution composition for cations and anions.

RATIONALE FOR THE ADOPTION OF TAXONOMIC SOIL SURVEY INFORMATION AS THE BASIS FOR ESTIMATING pH AND BASE SATURATION OF SIERRAN SOILS

Taxonomic soil surveys group soil bodies on the basis of physical and chemical properties which are, in turn, controlled by the environmental factors of soil formation. Examples of soil characteristics that are taxonomically significant and which directly or indirectly influence soil sensitivity to acid deposition are organic matter content, particle size distribution and clay content, percent base saturation, coarse fragment content, and depth.

Some chemical parameters which influence sensitivity are not taxonomically significant. Included in this group is exchangeable aluminum. Additional analyses are necessary to supplement the taxonomic database in these situations. However, because it is impractical to perform supplemental analyses on every taxonomic soil component within a 2-million-acre study area, chemical data required as model input often must be extrapolated from sampled components to approximate chemical characteristics of unsampled components.

The extrapolation of data from sampled to unsampled taxonomic components is based on soil correlation. Soil correlation involves consideration of soil physical and chemical properties and observable, taxonomically significant characteristics to group soils with

similar limitations for use and management. An underlying assumption of this study is that principles of soil correlation apply to grouping soils with respect to their response to acid deposition.

PROJECT OVERVIEW

The project includes four phases: soil survey data acquisition and database management; soil chemical characterization; computer program development, calibration, and validation; and data analysis and map production.

Order 3 soil survey is a reconnaissance level of resolution. The minimum area of contrasting soils recognized at the Order 3 level is roughly 50 acres. Order 3 soil survey information at 1:62,500 scale was obtained for the Tahoe, El Dorado, Sierra, and Sequoia National Forests. Order 3 information at 1:24,000 scale was obtained for the Stanislaus National Forest and for the Soil Survey of Sequoia National Park, Central Part (Huntington and Akeson, 1987). Additionally, approximately 106,000 acres within Yosemite, Kings Canyon, and Sequoia National Parks were mapped by NORTH STATE RESOURCES soil scientists at approximately 1:24,000 scale. The soil survey maps and a description of the technical methods are included in Appendix A.

Soil chemical characterization is based on lab analyses of one hundred sixty-seven samples taken from forty-three modal soil profiles throughout the study area. One hundred forty-four of the one hundred sixty-seven samples were analyzed under this research effort. Data for the remaining twenty-three samples are taken from Huntington and Akeson (1987). Locations of sampled soil pedons are given in Table 2. Lab data for analyzed profiles were extrapolated to unanalyzed profiles based on taxonomic similarities and soil correlation procedures. Chemical data are presented in Appendix B, Table B.9. Data sources are presented in Appendix B, Table B.9.

TABLE 2

LOCATION OF SAMPLED SOIL PEDONS

MAP UNIT SYMBOL	SOIL NAME	LOCATION
719CeC	CELIO	SE1/4 SE1/4 Sec 29, T21N, R13E
791FtE	TAHOMA	SE1/4 NW1/4 Sec 32, T19N, R16E
719JwF	JORGE	NE1/4 Sec 8, T15N, R16E
719LcE	LEDFORD	NE1/4 NE1/4 Sec 9, T2ON, R13E
719MiE	MEISS	NW1/4 NE1/4 Sec 12, T17N, R13E
719TbE	TALLAC	SW1/4 NE1/4 Sec 21, T17N, R16E
719TiE	TINKER	NW1/4 NW1/4 Sec 24, T17N, R14E
719WaE	WINDY	NW1/4 SW1/4 Sec 6, T18N, R12E
719WoG	WOODSEYE	NW1/4 SE1/4 Sec 30. T17N, R13E
724128	GERLE	NW1/4 SW1/4 Sec 2, T13N, R14E
724132	SMOKEY	NE1/4 SE1/4 Sec 33, T13N, R14E
724158	NOTNED	E1/2 NW1/4 Sec 5, TION, R17E
724162	LITHIC CRYUMBREPTS	SW1/4 NW1/4 Sec 2, TION, R16E
724216	WACA	SW1/4 SW1/4 Sec 7, TION, R17E
731101	ANDIC CRYUMBREPTS	Center Sec 35, T6N, R21E
731106	ENTIC CRYUMBR, M.D.	SW1/4 Sec 27, T6N, R21E
731116	GERLE F.,D	NW1/4 NW1/4 Sec 8, T2N, R19E
731147	INVILLE FAMILY	SE1/4 Sec 28, T4N, R18E
731163	LITHIC CRYOPSAMMENTS	NW1/4 SE1/4 Sec 27, T6N, R21E
731197	WINTONER FAMILY	NE1/4 Sec 9, T4N, R18E
750104	AQUIC DYST XEROCHREP	NW1/4 SE1/4 Sec 27, T5S, R24E
750113	LITHIC XEROPSAMMENTS	NW1/4 NW1/4 Sec 11, T6S, R25E
750115	CAGWIN FAMILY	NE1/4 NE1/4 Sec 12, T8S, R25E
750131	TYPIC XERUMBREPTS	NE1/4 SE1/4 Sec 35, T5S, R2E
750132	ENTIC CRYUMBREPTS	SE1/4 NE1/4 Sec 26, T7S, R26E
750158	SIRRETTA FAMILY	NW1/4 NW1/4 Sec 24, T10S, R27E
750162	STECUM FAMILY	SE1/4 SW1/4 Sec 1, T10S, R27E
750174	UMPA FAMILY	SW1/4 SW1/4 Sec 8, T5S, R24E
760311	MONACHE VARIANT	E1/2 SE1/4 Sec 31, T20S, R32E
760311	SEQUOIA MEADOW	
760409	SIRRETTA	SW1/4 SE1/4 Sec 15, T23S, R33E
760603	CANNELL	NW1/4 Sec 12, T21S, R34E
760609	TOEM	NW1/4 Sec 33, T20S, R34E
760612	JUMPE FAMILY	SW1/4 NE1/4 Sec 24, T23S, R33E
760613	BALD MOUNTAIN	SE1/4 Sec 3, T22S, R34E
760625	NANNY FAMILY	Center Sec 7, T24S, R32E
792AqF	AQUEPTS, FRIGID	NE1/4 SE1/4 Sec 29, T15S, R30E
792CaQ	CRYAQUEPTS	NW1/4 Sec 25, T15S, R30E
792EcF	ENTIC CRYUMBREPTS, L-SK, M	NE1/4 NW1/4 Sec 25, T15S, R30E
792JgoF	LITHIC XERUMBREPTS,S,M,F	NW1/4 SW1/4 Sec 28, T15S, R30E
792LeuD	LITHIC CRYUMBREPTS, L, M	NE1/4 NW1/4 Sec 25, T15S, R30E
792PxbD	PACHIC XERUMBREPTS, C-L,F	W1/4 Line Sec 28, T15S, R30E
792coF	TYPIC CRYORTHENTS	NE1/4 Sec 25, T15S, R30E

The lab data were used as the bases for calculation of the percent base saturation for each soil horizon in the soil profile or to a depth of 60 inches, whichever is shallower. The calculations were calibrated by adding known amounts of hydrogen ion to modal soil samples and recording the pH decrease with time. The depth-adjusted, average base saturation, along with slope and hydrologic soil group, were used as criteria to produce a 13-category relative ranking of soil map unit response to acid deposition. The 13 categories were aggregated into three broad classes and the boundaries of each class plotted on clear mylar registered to 1:62,500 scale USGS topographic maps. The resulting approximately 1 inch = 1 mile scale map of relative soil map unit sensitivity was reproduced using a vellum/blueline process.

STUDY LIMITATIONS

Limitations apply to each phase of the study. The boundaries of sensitive soil bodies are based on Order 3 information, which is a reconnaissance level of resolution. Reconnaissance level information is generally recognized as suitable for regional planning and for making broad comparisons of the characteristics of third order or larger watersheds.

The minimum area of contrasting soils recognized at the Order 3 level - that is, the minimum delineation - is approximately 40 acres. (The minimum delineation for the Tahoe National Forest and Sequoia National Park, Central Part, is smaller than 40 acres). Contrasting soil bodies smaller than the minimum delineation are included in larger bodies. Soil map unit boundaries are plotted by a combination of aerial photo interpretation and on-site verification. Areas without easy access are rarely visited, and as many as one third of the map unit delineations may not have been examined in the field. Often, soil series have not yet been established in upland areas, so the soil taxonomic components of the map units are classified at a higher (more general) level of taxonomy, typically the phase of soil family level. Finally, the map units at the Order 3

level are the more encompassing soil association and soil complex instead of the purer soil consociation.

Hydrologic soil group and map unit slope are criteria for ranking map units in terms of relative sensitivity. These parameters are included to distinguish between map units in terms of their response to short duration, high intensity precipitation events. These are qualitative criteria, and the magnitude of their influence on sensitivity is, to a large degree, indeterminate. Climatological and acid inputs are assumed constant in time and throughout the study area. In fact, microclimate, vegetation patterns, and other environmental characteristics too complex to map at the Order 3 level of resolution influence soil response, but are ignored in this study.

The estimation of soil pH and base saturation is limited by difficulty of extrapolating short term results to longer term processes. Because of its high cation exchange capacity, soil organic matter can be an effective buffer or a source of acidity. Litter and duff are not considered in estimating soil pH and base saturation in this study. This is because the presence and thickness of the litter layer is extremely variable and is not a criterion to differentiate between soils. Also, management activities such as timber harvesting and burning change the amount of litter and the contribution of the forest floor to acid buffering. Even if the thickness of the litter layer could be mapped, the map would be only a representation of the layer at a single, relatively brief point in time. In light of these constraints, the effect of this important source of buffering has been ignored. However, it is important to note that in situations where considerable duff or litter exists, the soil response to acide deposition might be considerably different than that predicted by this calculation.

Input for the calculation of soil response is based on lab characterization of one hundred sixty-seven samples from forty-three taxonomic components. The names and locations of the sampled components are listed in Table 2. Chemical data for unsampled profiles are

based on soil correlation which introduces an element of uncertainty into the calculated response.

Chemical data required to predict soil pH and base saturation are often not included in standard soil survey databases. For example, required data include soil pH, exchangeable bases, exchangeable Al^{3+}, and H^{+}. Exchangeable Al^{3+} and H^{+} were not available for all sampled horizons, and in these cases were estimated from soil pH and base status by regression analysis.

Other mechanisms which influence pH response and buffering were not incorporated into the calculation because the data were not available or because the process was not amenable to a functional relationship necessary for the program. Although the program can include an empirical correction for mineral weathering, differences among parent materials and changes in weathering rates accompanying pH changes could not be documented and weathering was not included in the pH and base status computations. Decomposition of organic matter may increase pH. However, because decomposition rates vary widely with temperature, moisture, soil microflora, microfauna, litter type, and management activities, the influence of organic matter decomposition was not included in the computations.

These constraints limit the calculation of absolute response of the study soils to acidic inputs. However, determination of an absolute response was not the intent of this study. Rather, the computations were used to determine a relative ranking of soils with respect to their response to acid deposition. The database provides a reference point for these soils. The boundary of the sensivity rankings can easily and inexpensively be recalculated with different inputs as required.

METHODS

SOIL SURVEY DATA ACQUISITION AND DATABASE MANAGEMENT

Order 3 soil survey information at 1:62,500 scale was obtained for the Tahoe, El Dorado, Sierra, and Stanislaus National Forests. Order 3 information at 1:24,000 scale was obtained for the Stanislaus National Forest and for the soil survey of Sequoia National Park, Central Part. Soil survey information for the National Forests was provided by the respective forests. The Soil Survey of Sequoia National Park, Central Part, was provided by Dr. Gordon Huntington. Additionally, approximately 106,000 acres within Yosemite, Kings Canyon, and Sequoia National Parks were taxonomically mapped by NORTH STATE RESOURCES soil scientists as part of this study.

Study area boundaries are shown in the Index to Map Sheets. Boundaries of the eight survey areas included in the study area can be determined by referring to the map unit sensitivity maps.

NSR applied National Cooperative Soil Survey (NCSS) procedures in mapping the parks. A description of the soil survey methods accompanies the soil survey manuscripts for these acres, included as Appendix A to this report.

To minimize distortion, soil map unit boundaries for most of the Forest Service mapping were digitized from the original mylar overlays used to produce published maps. Overlays for the Stanislaus National Forest and Sequoia National Park were unavailable so map unit boundaries were taken from published maps. NSR map unit boundaries were transferred from 1:24,000 scale mapping photos to identical scale USGS orthophotos. Boundaries were digitized from the orthophotos.

Digitizing was accomplished using Environmental System Research Institute, Inc., (ESRI) pc ARC/INFO, (Version 3.2), software. Digitizing hardware included Wyse 286, Compaq 386, and Compunet 386 computers with a 130 megabyte hard disk drive, and a Cal Comp 9100 36-inch x 48-inch backlit digitizing table. A Cal Comp 1044 8-pin plotter was used for map production.

Map unit descriptions and taxonomic unit descriptions (e.g., polygon attribute data) for the national forests were obtained in magnetic format from the Soil Conservation Service (SCS). These data and the attribute information for the national parks were summarized in a relational database using R-Base System V software.

The structure of the attribute database is similar to that of the State Soil Geographic (STATSGO) database developed by the SCS for planning on regional levels. The database consists of ten tables. Some tables describe map unit or taxonomic unit characteristics; others document the correlation process or show the sensitivity ranking of taxonomic units and map units. Each of the tables is described in the Results and Interpretation section of this report.

The tables are cross-referenced by a shared attribute, the map unit identification symbol, which is common to all tables.

The map unit identification symbol is the numeric or alphanumeric label which appears in each delineation of the sensitivity map. The first three digits of the label (e.g., 719, 724, 731, etc.) identify the state soil survey area (see Table 1 - Study Area Acreage by State Soil Survey Area); the following digits/characters are the map unit symbol within the state soil survey area. It is possible to integrate information from the ten tables to create hybrids by using relational commands.

The attribute data provided by the SCS had, in some cases, been generalized to accomplish objectives unrelated to this project. This situation is especially true for state

soil survey area 719, the Tahoe National Forest. In order to make the model input as representative as possible of soil conditions within the study area, considerable effort was spent replacing STATSGO data entries derived from Soil Interpretations Records (Form-SCS-Soil-5) from outside the survey area with information from pedons described within the study area and provided in the published soil surveys. Put another way, wherever possible, the information contained in the database is taken from modal pedons and the range of characteristics for modal pedons described within the study area. Modal pedons are soil exposures which typify the most commonly occurring expression of a taxonomic component.

SOIL SAMPLING AND SOIL CHEMICAL CHARACTERIZATION

Modal profile locations identified in the soil survey reports were plotted on 15-minute USGS topographic quadrangles. Components were stratified taxonomically and profiles were selected for sampling to provide a representative range of taxonomic characteristics within each survey area and for the study area as a whole. Accessibility also was a sampling criterion. Sampled profiles are identified in the SOURCE table included in Appendix B. Locations of sampled pedons are listed in Table 2.

Sampling was conducted during the summer and fall of 1987. Soil scientists traveled to the precise location of each modal profile and searched for evidence of excavation. Modal profiles were re-excavated; the soil scientist examined the profile and compared the newly exposed surface to the published description to verify the location. The soil profiles were re-described if the horizon thicknesses deviated from the published description by more than a few inches.

Approximately one-kilogram samples were obtained from each horizon and placed in plastic bags. Samples were dried at 60°C and screened to pass a 2mm (No. 10) sieve. The coarse fragments were discarded and all analyses were performed on the less than 2mm fraction.

Chemical characterization of soil proceeded in phases. Rather than determine a suite of soil parameters on all soil samples initially, thirty-six samples representing the range of chemical characteristics anticipated in the full sample set were analyzed to examine relationships among commonly determined soil chemical characteristics and chemical response to added acidity. At the same time, analytical methods were checked for accuracy and consistency. The remaining samples were analyzed when the data for the initial analysis were found to be internally consistent and the analytical results were reproducible within reasonable limits.

The pH of a 1:1 soil:water extract was measured for each of the thirty-six initial samples. Soil response to acidity was determined by adding 6 meq H^+ as nitric and as sulfuric acid to 100 grams dry soil. The 1:1 soil:solution pH was measured after 4 hours. The soils were maintained at constant temperature and the pH was measured a third time after 14 days. Selected samples were also treated with 0.1, 0.5, 1.0, 2.0 and 4.0 meq of H^+ per 100 grams and the pH measured at the same intervals.

Exchangeable acidity was measured by extraction with 1N KCl and titration with standard base. Extractable Al^{3+} was measured by back titration after addition of NaF (Thomas, 1982). Exchangeable cations were displaced by 1 N ammonium acetate and measured by atomic absorption (Thomas, 1982). The sum of exchangeable cations and exchangeable acidity was used to determine cation exchange capacity (Thomas, 1982).

Organic carbon was determined by the Walkley-Black method (Nelson and Sommers, 1982). Total N was measured by the Kjeldahl method (Bremner and Mulvaney, 1982). Sulfate adsorption was determined by adding sodium sulfate solutions to samples with initial concentrations of 0, 10, 25, 50, and 100 mg/l SO_4-S and determining the remaining SO_4-S after equilibration for 48 hours. Sulfate was determined by ion chromatography. Water soluble Ca, Mg, Na, and K as well as sulfate and nitrate were determined on selected samples prior to and following acid additions, by ICP and ion chromatography.

Selected samples were measured to determine the levels of iron and aluminum oxides extracted by oxalate, pyrophosphate, and dithionate (Bascomb, 1968; McKeague and Day, 1966; Mehra and Jackson, 1960). All samples were run in duplicate, and the analyses were repeated on soil pH several times. The average variation between separate runs on the initial 36 samples was 0.088 units with a range of 0 to 0.2 pH units. All analyses were compared against the control limits set in our laboratory.

COMPUTER PROGRAM DEVELOPMENT AND CALIBRATION

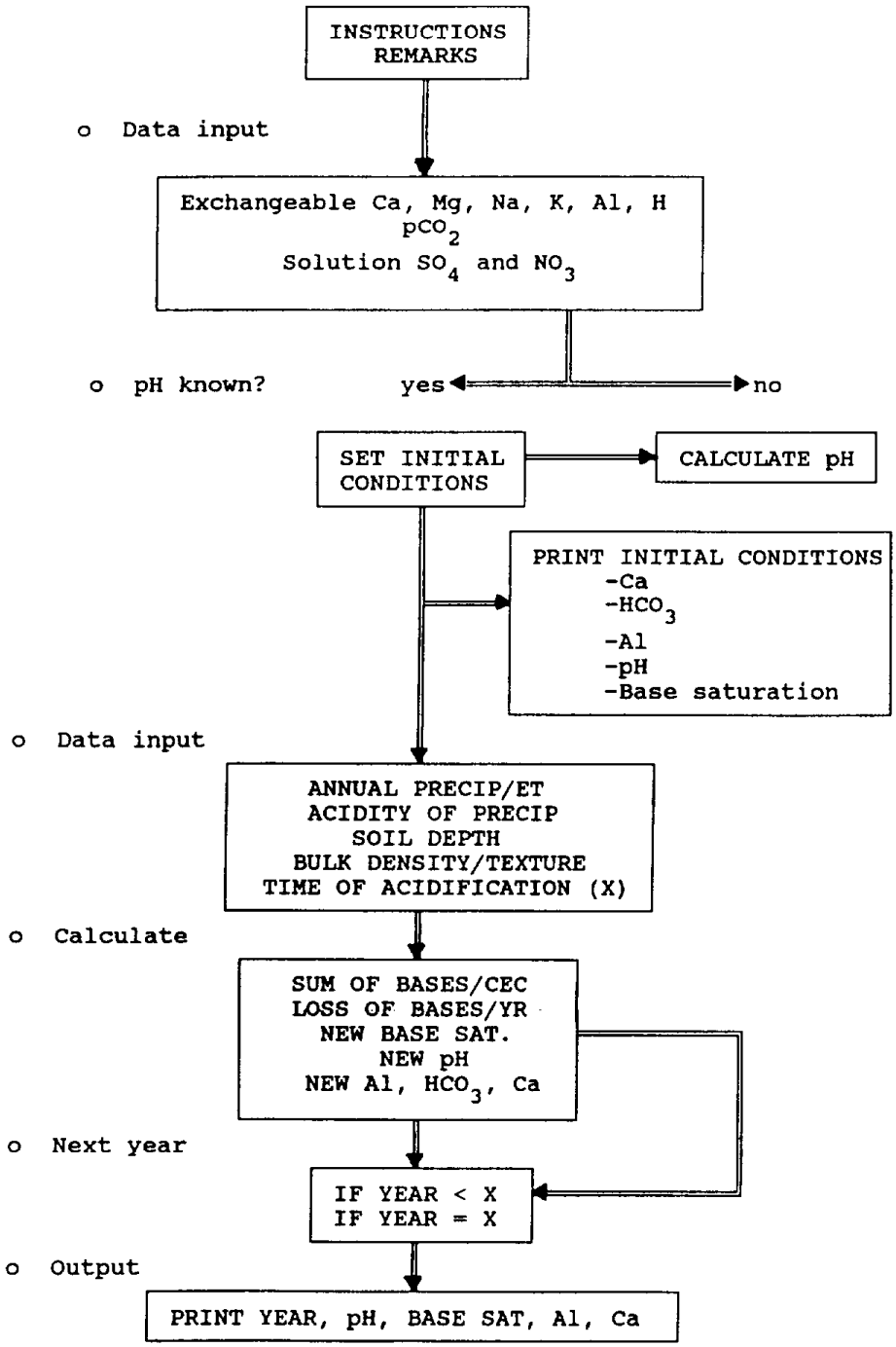
A flow diagram for the calculation of pH and base saturation is presented in Figure 1. First, soil chemistry data are input for exchangeable cations and partial pressure of carbon dioxide. A carbon dioxide partial pressure of 0.005 atmospheres was chosen to represent the increased level of carbon dioxide known in soils. This value has been used in other calculations (Bloom and Grigal, 1985) and is consistent with the level of carbon dioxide found in alpine soils (Solomon and Gerling, 1987). Estimates of soil solution nitrate and sulfate are required when the initial soil pH is unknown. The exchange composition is determined, base saturation calculated, and pH determined if it is an unknown. The pH is calculated in a manner similar to that described by Reuss and Johnson (1985) in which the chemical expressions outlined previously are combined in an electroneutrality expression of the form:

$$3(Al)^{3+} + 2[(Ca)^{2+} + (Mg)^{2+}] + (K) + 2(Al(OH)^{2+}) + (Al(OH)_2^{+}) + H^{+} =$$
$$(HCO3^{-}) + 2(SO_4^{2-}) + (NO_3^{-}) + (Cl^{-}).$$

The equation is rearranged in terms of pH and the resulting fifth order polynomial is solved for pH using a Newton-Raphson numerical technique. Once the pH is solved, aluminum speciation and alkalinity are computed. These data are then used to solve the mass balance expressions for cation exchange which will predict changes in soil solution cation concentrations. This part of the calculation uses the available chemistry data to set

FIGURE 1

FLOW DIAGRAM FOR PH AND BASE SATURATION CALCULATION



the initial soil conditions in terms of units compatible with the acidification routines that follow. The output of initial conditions follows. This routine is useful for calculating soil pH under conditions where the pH is unknown or suspect.

Precipitation and evapotranspiration data are input next. Values of 100 cm and 50 cm were chosen for precipitation and evaportranspiration, respectively. Rainfall and snow accumulation are quite variable in the study area and these values where considered to be within the variation encountered in the survey area (Major, 1988). Other values could be substituted, but the relative rankings would change very little. Acid deposition loading was chosen to be 0.3 kmol H^+/ha/yr, which is higher than current wet deposition rates in California. However, a high value was intentionally selected to distinquish between the responses of different soils. In light of the significant contribution of dry deposition, a loading of 0.3 kmol/ha/yr is not unreasonable. Effective soil depth of the horizon (corrected for coarse fragments), bulk density, and the time of acidification are all possible variables in the calculation. A time of 50 years and bulk density of 1.4 gm/cm^3 were chosen.

The computer program is similar to that proposed by Bloom and Grigal (1985) and contains the following assumptions. Sulfate is treated as a mobile anion and therefore not adsorbed by the soil. Although data for sulfate adsorption were obtained for the thirty-six initial samples, no straightforward and reliable prediction of sulfate adsorption can be made with commonly available data. As more sophisticated analyses become available or this process is better understood, the effects of sulfate adsorption can be incorporated into the program.

Second, all horizons are treated as surface horizons. The chosen acid inputs are imposed on each horizon without regard to its location in the profile. The model can be made more dynamic by changing incoming precipitation acidity to lower soil horizons to account for neutralization by the surface horizon.

Third, the properties of the soils are considered to be in a steady state condition. The pH, sum of bases, and base saturation represent an integration of rates of soil weathering, biocycling, additions of organic acids, and leaching of cations from the surface soil. With acidic deposition, the steady state is disturbed and the quantity of exchangeable bases is decreased. Fourth, the effective acidity in wet or dry deposition = $H^+ + NH_4^+ - NO_3^-$. The uptake of a mole of nitrate ions by plant roots results in the release of a mole of basicity. Because of this, nitric acid has no effect in acidification of soils in which plants are growing. Fifth, the volume of water flowing downward from surface horizons is equal to precipitation-evapotranspiration. Sixth, the partial pressure of carbon dioxide in the soil atmosphere is .005 atmosphere (Bloom and Grigal, 1985; Solomon and Gerling, 1987). The last assumption is that soil pH is estimated very well from lab data describing base saturation (BS) by the following expression:

$$pH = pKa + n\log (BS/(1-BS)$$

Where:

pKa = the apparent acidity constant for a soil,
n = an empirical constant, and
BS = the base saturation.

This equation describes a sigmoidal variation of pH with BS. This form of other extended Henderson-Hasselbach equation has been successfully applied to the titration of weak acid resins, extracted soil organic matter and peats.

In the computer program, experimentally determined pKa and n parameters were generated for the soils in the study area using laboratory data for the initial 36 samples. These data gave a value of 5.55 for pKa over a pH range of 6.4 to 4.8. Therefore, soil pH values outside of this range may not be as well described by the computer program.

The acidification routine proceeds where the loss of bases is calculated on a annual basis by:

$$S = I - A - C$$

where S is the sum of the change in exchangeable bases, I is the effective acidity in wet and dryfall, A is the acid leached from the soil horizon, and C is the decrease in bicarbonate due to the decrease in soil solution pH. The value for A is determined from:

$$A = (3 \times (Al^{3+}) + 2 \times (Al(OH)^{2+}) + (H^{+}) \times (Precip\text{-}ET) \times 100$$

where the pH dependent value for Al^{3+} is computed as described earlier. "Precip" is the annual precipitation and "ET" is the annual evapotranspiration.

The decrease in bicarbonate weathering, C, is given by:

$$C = ((HCO_3)_0 - (HCO_3)) \times (Precip\text{-}ET) \times 100$$

where $(HCO_3)_0$ is the initial bicarbonate concentration and HCO_3 is the bicarbonate at the beginning of the computation year.

At the end of each year, a new sum of bases is calculated by subtracting S from the sum of bases for the previous year. A new value for pH is calculated according to the base saturation relationship, new initial conditions are set, and the next year of computation begins. For each year of computation, the program outputs the year, the pH, and the base saturation. Additional output can be requested by exercising the appropriate options. These include soluble aluminum, calcium, bicarbonate and soil solution alkalinity.

In addition to the above routines, the program will consider mineral weathering. Mineral weathering is represented by the following kinetic expression:

$$r = k(H^{+})^{x}$$

where r is the rate of dissolution, k is the apparent rate constant, and x is a constant for a given mineral which generally ranges from 0.5 to 1.0. However, as previously mentioned, there is no provision in the current calculation for changes in weathering rates as pH decreases. Information on the appropriate values for x in these soils is also not available. Therefore, weathering has not been included in the calculations. This omission will affect the relative ranking only if weathering varies significantly among the soil bodies.

The program was calibrated with the soil chemistry data from the thirty-six sample subset which was collected to represent the range of soil properties throughout the study area. The most important calibration was with respect to the pH-based saturation relationship previously described. The range of pH in the initial sample (4.8 to 6.4) sets the range of initial soil pH for which the program has been developed.

RESULTS AND INTERPRETATION

SOIL MAP UNIT DATABASE

The soil map unit attribute database is included in Appendix B and consists of ten tables. Map unit and taxonomic unit characteristics are arranged in columns; map unit identification labels are arranged in rows. The hierarchical structure of the database and a description of the function and information contained in each table follow:

Table/Column	Function

MAPUNIT: lists map unit name in ascending alphabetical or numeric order by map unit identification label.

includes columns:

muid	-	map unit identification label; the first three digits indicate the State soil survey area and do not appear on the sensitivity map; the remaining digits/characters identify map units within each survey area and do appear on the sensitivity map;
muname	-	map unit name

MURANK: lists map units by soil survey area in ascending order of sensitivity; provides map unit names and acreages.

includes columns:

muid;		
muname;		
murank	-	map unit sensitivity rank;
muacres	-	map unit acreage

COMPED: describes map unit composition by map unit identification label and taxonomic component name.

includes columns: muid;
compname - taxonomic component name;
slopel - lower percent slope limit for component;
slopeh - upper percent slope limit for component;
hydgrp - SCS hydrologic soil group

COMPTAX: lists taxonomic classification by taxonomic component name (e.g., compname).

includes columns: compname;
class - soil taxonomic class

LAYER: describes soil profile horizons for each taxonomic component by map unit label; these data are the basis for the effective depth calculations used as model input.

includes columns: muid;
compname;
layernum - orders horizons, beginning with the surface;
laydepl - depth to upper horizon boundary, inches;
laydeph - depth to lower horizon boundary, inches;
texture - range of USDA soil textures known to occur;
inch3l - lower limit of weight percentage of whole soil retained on a 3-inch sieve;

inch3h - upper limit of weight percentage of whole soil retained on a 3-inch sieve;

no10l - lower limit of weight percentage of whole soil passing a standard No. 10 sieve;

no10h - upper limit of weight percentage of whole soil passing a standard No. 10 sieve

SOURCE: assigns a source number to each sample analyzed in this project and to laboratory data developed by Huntington and Akeson for the Sequoia NP, Central Part survey; source number are used in the LABDATA table to identify the source of lab data for unsampled horizons.

includes columns: muid;
compname;
layernum;
laydepl;
laydeph;
source - alphanumeric or numeric code which indicates the soil survey area, map unit symbol, and layer number for each analyzed horizon

PRNTHOR: identifies the horizon nomenclature and parent material for each mineral horizon.

includes columns: muid;
compname;
layernum;
laydepl;
laydeph;

horizon - major horizonation taken from modal soil profile descriptions;

prntmat - soil parent material (V = extrusive igneous; GRN = intrusive igneous; MTS = metamorphosed sedimentary; MTV = metamorphosed igneous; MIX = mixed parent materials)

SENRANK: lists taxonomic components in ascending order of the adjusted average percent base saturation simulated by the Sierran soil acidification model after 50 years.

includes columns: compname;

adav%bs - simulated adjusted average percent base saturation, 50 years

LABDATA: provides actual or correlated laboratory data for each mineral horizon; these data are used as model input.

includes columns: muid;

compname;

layernum;

laydepl;

laydeph;

source - refer to the SOURCE table for the origin of lab data for unanalyzed horizons;

pHi - initial 1:1 soil: solution pH;

HH^{+} - Exchangeable hydrogen ion, meq/100gm soil;

Al^{+++} - exchangeable aluminum, meq/100gm soil;

Ca^{++} - exchangeable calcium, meq/100gm soil;

Mg^{++} - exchangeable magnesium, meq/100gm soil;

K^+	-	exchangeable potassium, meq/100gm soil;
Na^+	-	exchangeable sodium, meq/100gm soil;
% oc	-	percent organic carbon;
cec	-	cation exchange capacity, meq/l00gm soil

DELTAPH: describes the change in 1:1 soil:solution pH with time following the addition of 6 meq H^+ as nitric and as sulfuric acid.

includes columns: compname;
layernum;
laydepl;
laydeph;
pHi;

pH1s	-	soil solution pH four hours after addition of 6 meq H^+ as sulfuric acid;
pH2s	-	soil solution pH 14 days after addition of 6 meq H^+ as sulfuric acid;
pH1n	-	soil solution pH four hours after addition of 6 meq H^+ as nitric acid;
pH2n	-	soil solution pH 14 days after addition of 6 meq H^+ as nitric acid

SOIL CHEMICAL CHARACTERIZATION

Results of the particle-size analyses and the chemical characterization of the 482 horizons recognized in the study area are presented in the LABDATA and DELTAPH tables, included in Appendix B. Values for initial pH ranged from 4.4 to 6.85. Base saturation (sum of exchangeable cations/sum of exchangeable cations plus exchangeable H^+ and Al^{3+}) ranged from .11 to .99. Organic carbon ranged from 0.11 percent to 12.5 percent;

exchangeable Ca^{2+} ranged from less than the detection limit to 23.8 meq/100gm soil. Concentrations of Mg^{2+}, K^{+} and Na^{+} were undetectable in some horizons. The total exchange capacity (sum of bases and H^{+} and Al^{3+}) varied from 1.5 to 60.3 meq/100gm of soil. Sulfate adsorption at the 100 mg/l initial level varied from 0 to 450 mg/kg of soil in the subset of thirty-six samples analyzed initially.

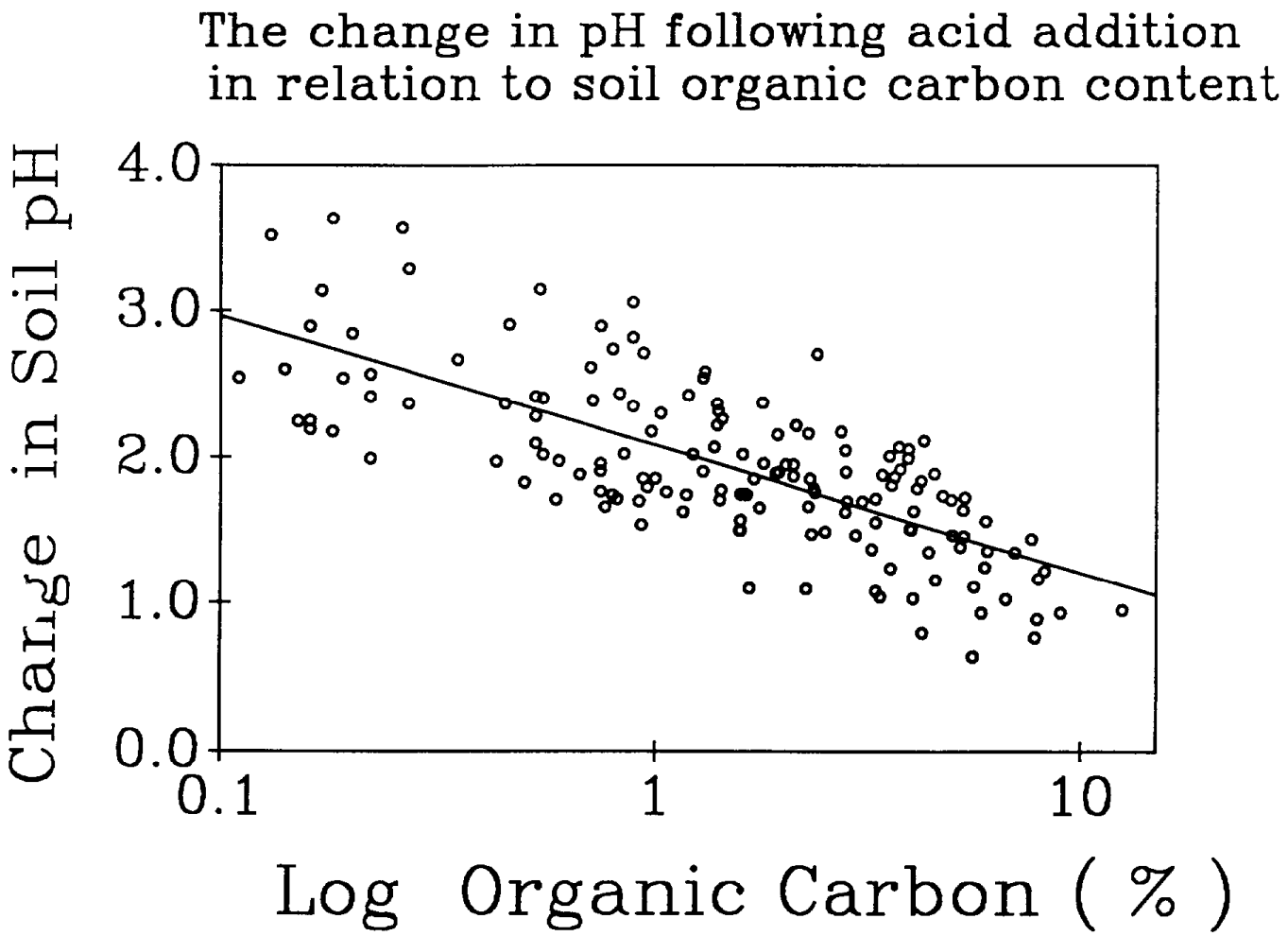
Buffering capacity would be expected to vary considerably among the soils and horizons because of the variability in these chemical parameters. Clay plus silt content is another important variable which influences soil buffering. However, clay plus silt content varied little among horizons in the study area, partly because of the homogeneity of the soil parent materials.

The addition of 6 meq H^{+}/100g soil as nitric acid resulted in substantial pH decreases. The lowest pH induced by this acid addition was 2.9 while the highest pH after acidification was 5.6. As shown in Figure 2, the change, in pH (e.g., initial pH - final pH) resulting from the addition of H^{+}, (ie. the delta pH) was related to organic carbon content. Addition of 6 meq H^{+}/100g soil as sulfuric acid induced a pH change about 0.5 pH unit less than that obtained from nitric acid addition.

The change in pH after acid addition on the final pH after 2 weeks could be used as a direct measure of acid sensitivity. However, this direct experimental approach is not suited to the large number of soils sampled and to those not accessible to direct manipulation. Nonetheless, experimental pH changes were used as an index of sensitivity and the influence of soil properties on sensitivity was examined by regression analysis.

Delta pH after 2 weeks was well correlated with organic matter and the sum of exchangeable bases for the A horizon samples. This relationship was weaker for the B and C horizons.

FIGURE 2


The change in pH following acid addition
in relation to soil organic carbon content
Change in Soil pH
4.0
3.0
2.0
1.0
0.0
0.1
1
10
Log Organic Carbon (%)

For the A horizon:

$$pH_{2N} = 3.35 - 0.089\ [(T_o - 4.5) \times OC] + 0.047 \text{ sum bases}$$

$r^2 = 0.72$, $n = 66$ where pH_{2N} is the pH for nitric acid additions after 2 weeks, and OC is organic carbon.

For the B horizon:

$$pH_{2N} = 3.28 - 0.194\ [(TO - 4.5) \times OC] + 0.025 \text{ sum bases}$$

$r^2 = 0.60$, $n = 40$

For the C horizon:

$$pH_{2N} = 3.30 - 0.126\ [(T_o - 4.5) \times OC] + 0.018 \text{ sum bases}$$

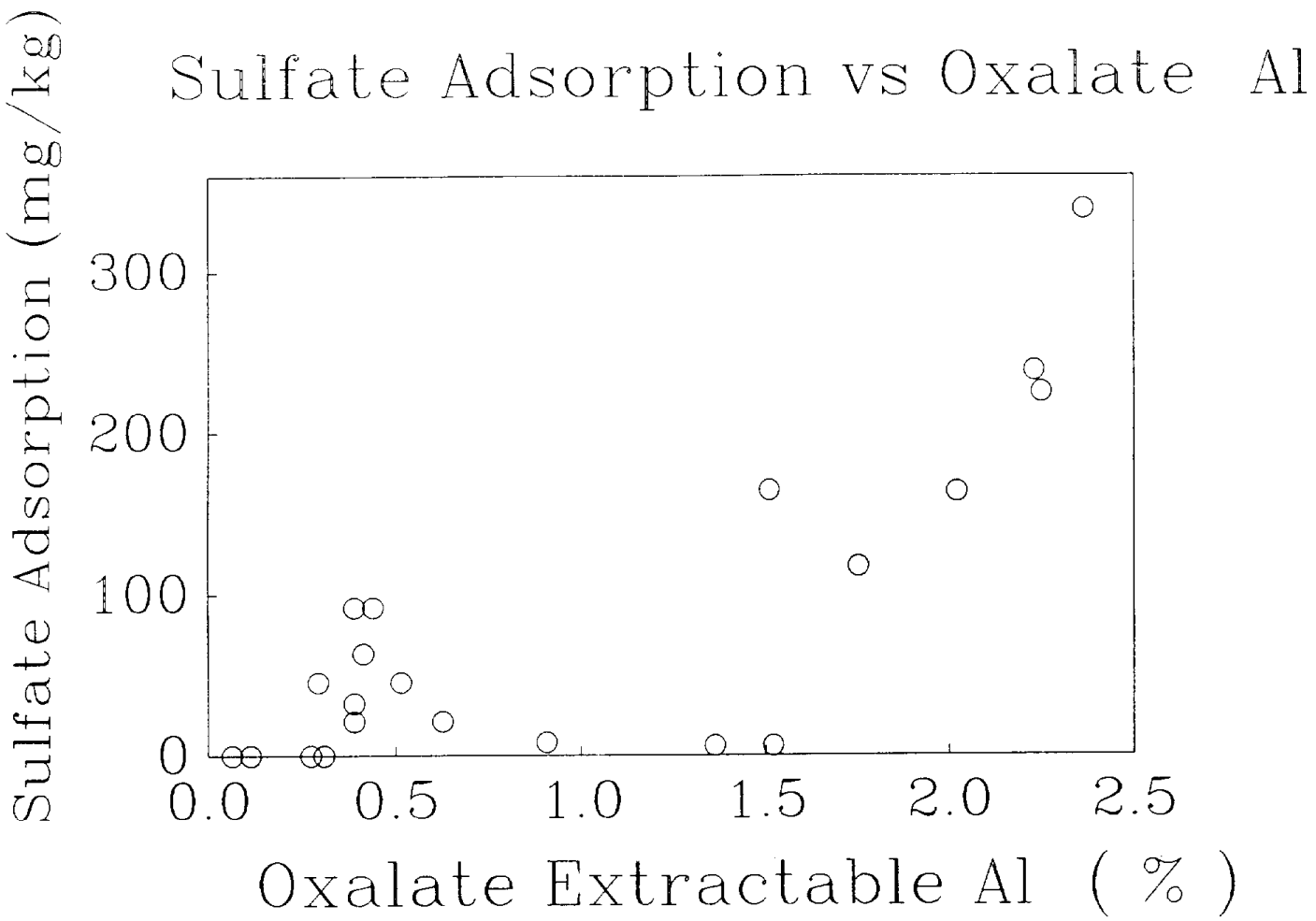
$r^2 = 0.34$, $n = 47$

In the A horizon, organic matter or an undetermined property related to organic matter was strongly controlling soil response to acid addition. Delta pH was strongly related to the initial pH in the C horizons ($r^2 = 0.809$, $n = 47$), and less well related in the B and A horizons, ($r^2 = 0.615$ and 0.28, respectively).

Sulfate adsorption and extractable iron and aluminum were determined for some of the thirty-six sample subset initially analyzed. Sulfate adsorption varied from 0 to 450 mg/kg among the samples, but was not related to commonly determined soil characteristics such as pH, base saturation or particle-size distribution. As shown in Figure 3, sulfate adsorption was reasonably well related to oxalate-extractable Al.

Based on laboratory analyses and regression analyses, soil pH changes were related to organic matter content, initial pH, and the sum of exchangeable bases. These parameters are considered implicitly or explicitly in the acidification program.

FIGURE 3


Sulfate Adsorption vs Oxalate Al
Sulfate Adsorption (mg/kg)
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Oxalate Extractable Al (%)

RELATIVE RANKING OF SOIL TAXONOMIC UNITS AND SOIL MAP UNITS BY SENSITIVITY RESPONSE

Data from the LABDATA and LAYER tables were used as input for the calculation of percent base saturation and adjusted-average percent base saturation. An input of 0.3 kmol H^+/ha/yr was chosen for a 50-year period as discussed previously. Adjusted-average percent base saturation is defined as the weighted-average percent base saturation for horizons from modal soil profiles, base saturation values for horizons being weighted on the basis of horizon thickness. The average value is adjusted based on the data contained in the LAYER table to compensate for coarse fragments which are assumed inert. The resulting values for adjusted-average percent base saturation are presented in ascending order in the SENRANK table in Appendix B.

Previous studies have demonstrated that at about 15 percent base saturation, solution Al^{3+} increases dramatically with further reductions in exchangeable non-acidic cations (Reuss 1983). At 15 percent base saturation, pH is also in a region where soluble Al^{3+} generally increases rapidly with further acidification. Therefore, a base saturation of 15 percent after 50 years of acidification was chosen as the separation between sensitive soils and non-sensitive soils. Eighty-eight of the 162 taxonomic units included in the study area - about 54 percent - are sensitive by this criterion.

A fourteen-cell matrix was constructed to rank soil map unit sensitivity. Sensitivity criteria included simulated adjusted, average-percent base saturation (from the SENRANK table), hydrologic soil group, and percent slope.

Previous studies have cited the influence of soil permeability on watershed response to acid deposition (Lund, et al., 1987). Hydrologic soil group and slope are included as sensitivity criteria because these are commonly reported taxonomic unit and map unit attributes (respectively) which permit comparison of map units in terms of the length of time during which precipitation may react with soil and the degree to which reactions involving the solid and liquid phase approach equilibrium.

A hydrologic soil group is a group of soils having the same runoff potential under similar storm and cover conditions. Four main groups are defined: A, B, C, and D. Soils in group A have high infiltration rates when thoroughly wetted, and, by inference, rapid subsoil permeability. Soils in group D have low infiltration rates, and are, by inference, slowly permeable or shallow.

The hydrologic soil group for the dominant taxonomic unit was applied to the entire map unit. Map units composed of more than 50 percent miscellaneous land types were placed in cell 13; water bodies were placed in cell 14. The matrix table is presented in Table 3.

Broad soil map unit sensitivity classes were defined by aggregating the contents of the 14-cell matrix as follows:

Cell Numbers	Sensitivity Class	Acres	Percent of Study Area
1, 2, 3, 4, 5	Least Sensitive	527,564	24.9
6, 7, 8	Moderately Sensitive	380,677	18.0
9, 10, 11, 12, 13	Most Sensitive	1,183,601	55.9
14	Water	24,586	1.2
		2,116,428	100.0

TABLE 3

MAP UNIT SENSITIVITY CRITERIA
(Number of Map Units per Cell)

Map Unit Slope	<35%		30 - 50%		<50%	
Hydrologic Soil Group	A + B	B + C	A + B	B + C	A + B	B + C
Sensitive Soils Comprise Less Than 50 Percent of Unit	Cell#1 (42)	Cell #2 (6)	Cell#3 (39)	Cell#4 (3)	Cell#5 (18)	Cell#6 (3)
Sensitive Soils Comprise at Least 50 Percent of Unit	Cell#7 (29)	Cell#8 (34)	Cell#9 (20)	Cell#10 (18)	Cell#11 (24)	Cell#12 (39)
Miscellaneous Land Types Comprise at Least 50 Percent of Unit	Cell#13 (86)					
Water	Cell#14 (8)					

MAP OF SOIL MAP UNIT SENSITIVITY TO ACID DEPOSITION

The digitized soil map unit delineations were shaded according to the broad sensitivity classes. The map was plotted at 1:62,500 scale on clear mylar. The 18-inch by 24-inch mylar overlays were registered to identical scale USGS 15-minute quadrangles, and vellum reproductions were made from the composites. Blueline reproductions were then made from the vellums which show individual soil map unit boundaries identified by the map unit symbol within each soil survey area. Individual soil survey area boundaries are also shown. The graphic data are superimposed on USGS topographic and cultural data.

Portions of forty-five individual 15-minute quadrangles are required for coverage of the 2,116,428-acre study area. A 1:85,700 scale (1 inch ~ 16 miles) index to map sheets is included in the map envelope attached to this report. Also included in the map envelope is one of the forty-five individual map sheets which serves as a sample of the complete map.

DISCUSSION

The sensitivity of soil taxonomic units to acid deposition can be assessed in different ways. There are long-term reactions and short-term reactions which attenuate acid inputs. Most approaches have emphasized the short-term responses because the longer-term responses are more difficult to quantify and predict. These difficulties arise because experimental data are lacking, and the mechanisms of long-term response are extremely complicated. Wyles (1986) summarized the approaches taken by several researchers and developed a sensitivity classification for Sierran soils based on several soil properties including initial pH, cation exchange capacity, base saturation, organic carbon, soil depth, and parent material. LeVine and Ciolkosk (1988) found base saturation, sum of exchangeable bases, and soil pH to be related to soil sensitivity in Pennsylvania.

The results of this study indicate that base saturation, pH, parent material, cation exchange capacity, soil depth, and organic carbon all influence soil response to acid deposition. Organic carbon was more important in the surface horizons and initial pH was more important in the lower horizons. A combination of initial pH, sum of the base cations, and organic carbon was strongly related to the decrease in pH after acid addition in the organic-rich A horizon samples, but the relationship was less predictive in the lower horizons.

The Sierran soil acidification model was developed to predict pH and base saturation given acid additions. The model uses pH, base saturation, exchange capacity and developed exchange relationships to perform the simulation. Effective soil depth (soil depth minus depth occupied by coarse fragments) is also an important input to the model.

Any classification system which ranks a continuous variable must arbitrarily divide the data set into categories. One option would be to present the rank of each soil relative to all

others and avoid the complications of selecting classes. This approach is not well suited to cartographic representation. We therefore chose to divide the soils into three sensitivity classes based on average-percent base saturation. Average-percent base saturation was chosen as an index of taxonomic unit sensitivity because it is related to pH and aluminum saturation.

Reuss (1983) and Reuss and Johnson (1986) have demonstrated that an abrupt transition in soluble Al occurs around 5 to 15 percent Ca^{2+} saturation. Depending on assumptions and solution parameters, soluble Al^{3+} increases rapidly as exchangeable Ca^{2+} decreases below this range. Soluble Al^{3+} and the attendant low Ca, Mg, and K saturation and other nutritional changes have been implicated in a number of processes and factors affecting forest growth and vigor (cf. Binkley, et al., 1989). Fifteen percent base saturation was selected to distinguish between sensitive and less sensitive soils on this basis.

Base saturation was calculated using a computer program as described earlier. The program used acid inputs of 0.3 kmol H^+/ha/yr for a 50-year period. Depositional rates vary within the study area, and the chosen value is higher than contemporary wet deposition inputs. A high input value was intentionally chosen to stress the soil system and distinguish between the responses of individual soil types. Dry deposition is substantial; Air Resources Board measurements suggest dry deposition may be many times the wet deposition (ARB, 1986). A value of 0.3 kmol/ha/yr is reasonable given the study objectives, the potential contribution of dry deposition, and values measured elsewhere. Finally, simulations generated by our computer program also generally agree with the direct measurement of response to acid additions in the laboratory. Simulations with lower acid inputs for shorter time periods resulted in nearly identical ranking among the soils.

To summarize, 88 of the 162 taxonomic units recognized in the study area are considered sensitive based on the simulated 50-year percent base saturation criterion. Map unit slope and hydrologic soil group are combined with the taxonomic unit criterion to define map

unit sensitivity. Three hundred sixty-nine (369) map units have been defined. Using the present system of classification, 188 map units (roughly 29 percent) are considered least sensitive; 66 map units (roughly 18 percent) are considered moderately sensitive; 187 map units (roughly 51 percent) are most sensitive.

Acreages and percent of the study area occupied by each sensitivity class are given in the preceding section. Approximately 56 percent of the survey area - 1,183,601 acres - is included in the most sensitive class. Over 650,000 acres of the most sensitive class are map units of which at least 50 percent is a miscellaneous land type (e.g., rock outcrop, talus, glacier, etc.). It is reasonable to assume that the acreage assigned to the most sensitive class would decrease if more detailed mapping which permitted a differentiation between soil and nonsoil were completed.

Nonetheless, the study demonstrates that Sierran soils of the frigid and cryic soil temperature regimes are generally sensitive to strong mineral acid addition. With few exceptions they are coarse textured and low in exchange capacity. Often they are lithic or moderately deep and have coarse fragment contents that exceed 35 percent of the whole soil by weight. These properties dispose the soils to a low buffering capacity, and this was demonstrated in the laboratory.

There were relatively small differences in texture among the soils, and this limited the usefulness of the exchange capacity as a predictor of buffering. If the frigid and cryic soils were compared to the more variable soils of the mesic and thermic soil temperature regimes, it is likely that texture and cation exchange capacity along with other soil properties would be distinguishing characteristics.

In the present study area, the sum of exchangeable bases, organic matter content, and effective soil depth were the most important variables affecting soil response to acid deposition. Parent material was also generally indicative of buffering capacity. Soils

weathered from extrusive igneous parent materials were less sensitive than their intrusive igneous counterparts.

The present sensitivity ranking system appears to work well on cryic and frigid Sierran soils for which commonly measured chemical and physical properties are known. The ranking system should work on more variable soils, but additional calibration of the calculation would be required. Modification and refinement of the map unit criteria is also required before the classification system can be applied outside the present study area.

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LIST OF PUBLICATIONS RELATED TO THIS RESEARCH

TITLE: pH Buffering of Frigid and Cryic Sierra Nevada Soils

AUTHORS: R.J. Zasoski, W.J. Walker, and J.B. Chung,
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PRESENTATION: Poster Session, American Society of Agronomy
Annual Meeting, November 27 to December 2, 1988

ABSTRACT:

Ten modal profiles representing a range of soils from the central California Sierra Nevada mountains were evaluated for pH buffering against strong mineral acids. Thirty-six horizons from the cryic and frigid soil zones were selected to represent a range of parent material and soils characteristics in this region. In these soils organic carbon ranged from 1.3 to 92 g kg^{-1}, and initial pH varied from 4.7 to 6.4. Exchangeable acidity ranged from 0.1 to 2.3 cmol kg^{-1}. Decreased pH associated with nitric and sulfuric acid additions was related to parent material, initial pH and sulfate adsorption characteristics. These parameters in addition to exchangeable and soluble cations and sulfate adsorption were used to develop and calibrate a short-term pH buffering model. The equilibrium model was tested on 30 additional profiles (96 horizons) and found to describe the buffering quite well. The model and output will be presented.

GLOSSARY OF TERMS

adjusted average percent base saturation - The base saturation, expressed in decimal terms, for the whole profile or to 60 inches depth, whichever is shallower, calculated from the average of the base saturation values for individual soil horizon, weighted on the basis of horizon thickness and coarse fragment content.

adsorption - The process by which atoms, molecules, or ions are taken up and retained on the surfaces of solids by chemical or physical binding, e.g. the adsorption of cations by negatively charged minerals.

percent base saturation - The extent to which the adsorption complex of a soil is saturated with alkali or alkaline earth cations expressed as a percentage of the cation-exchange capacity, which may include acidic cations such as H^+ and aluminum.

buffering capacity - The ability to neutralize both acids and bases in solution.

bulk density - The mass of dry soil per unit bulk volume.

cation-exchange capacity - The sum of exchangeable cations that a soil, soil constituent, or other material can adsorb at a specific pH. It is usually expressed in milliequivalents per 100 grams of exchange.

cryic soil temperature regime - A soil temperature regime that has mean annual soil temperatures of more than 0C but less that 8C, more than 5C difference between mean summer and mean winter soil temperatures at 50cm, and cold summer temperatures.

pH - The negative of the logarithm of hydrogen ion concentration in aqueous solution: low pH is acid, high pH is alkaline, pH of 7 is neutral.

differentiae - The distinguishing attribute of any entity.

digitized - Computer process whereby cartographic information is stored, manipulated, and retrieved by assigning spatial coordinates to graphics elements and linking these coordinates to a descriptive database.

duff - Decaying vegetable matter covering forest ground.

effective depth of soil horizon - The depth of mineral soil, adjusted to compensate for the volume occupied by coarse fragments larger than 2mm.

exchange capacity - The total ionic charge of the adsorption complex active in the adsorption of ions. See cation-exchange capacity.

exchange acidity - The titratable hydrogen and aluminum that can be replaced from the adsorption complex by a neutral salt solution.

exchangeable ions - Exchangeable ions adsorbed by a soil, clay, or organic matter.

frigid soil temperature regime - A soil temperature regime that has mean annual soil temperatures of more than 0C but less than 8C, more than 5C difference between mean summer and mean winter soil temperatures at 50cm, and warm summer temperatures.

hydrolysis - Chemical decomposition in which a compound is divided into other compounds by taking up the elements of water.

hydrologic soil group - A group of soils having the same runoff potential under similar storm and cover conditions.

infiltration rate - The rate at which water enters the soil.

ion chromatography - Separation of ions by a method in which the ions in solution are separately adsorbed in colored layers of an adsorbent to facilitate the analysis of mixtures.

mapping unit - A cartographic aggregation of soil taxonomic units associated with non-soil land features including slope, parent material, vegetation, etc. Soil surveys are composed of individual mapping units.

mesic soil temperature regime - A soil temperature regime that has mean annual soil temperatures of 8C or more but less than 15C, and more than 5C difference between mean summer and mean winter soil temperatures at 50cm.

minimum delineation - The minimum area for which differing soil or landscape conditions are recognized. The minimum delineation is largely determined by the scale of the mapping photography.

miscellaneous land type - A mapping unit for areas of land that have little or no natural soil, that are too nearly inaccessible for orderly examination, or that for any reason it is not feasible to classify the soil.

modal pedons - The actual soil body which typifies the central concept of a taxonomic unit (i.e., the most common condition of the soil) in terms of diagnostic criteria including presence and arrangement of horizons, coarse fragment content, soil parent material, etc.

The modal pedon is identified after studying many individuals to determine the range of characteristics.

orthophotos - Stereoscopic photographs that have been altered to minimize scale distortion.

parent material - The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of soils is developed by pedogenic processes.

relational database - A collection of data items which are referenced to one another by a shared attribute; relational databases are well-suited to determining relationships among data elements.

runoff - That portion of the precipitation on an area which is discharged from the area through stream channels and sheet flow.

soil association - (i) A group of defined and named taxonomic soil units occurring together in an individual and characteristic pattern over a geographic region. (ii) A mapping unit used in which two or more defined taxonomic units occurring together in a characteristic pattern are combined because the scale of the map or the purpose for which it is being made does not require delineation of the individual soils.

soil complex - A mapping unit used where two or more defined taxonomic units are so intimately intermixed geographically that it is undesirable or impractical, because of the scale being used, to separate them. A more intimate mixing of smaller areas of individual taxonomic units than that described under **soil association.**

soil consociation - A mapping unit used in which a single taxonomic unit is clearly the most common, typically occupying up to 80 percent or more of each delineation.

soil correlation - The process of determining the range of soil characteristics appropriate to a taxonomic unit; implicit in the process is the extension of data by inference and thus achieve a conjectural knowledge of the unknown.

soil family - The lowest (most restrictive) taxon of the USDA Soil Taxonomy; family criteria include texture, minerology, reaction, soil temperature, and thickness of horizons.

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 numbers of organisms present, degree of acidity or alkalinity, etc.

soil solution - The aqueous liquid phase of the soil and its solutes.

soil taxonomy - A system of classification which aggregates soils in categories to facilitate study and comparison.

Solum - The upper and most weathered part of the soil profile; the A and B horizons.

taxonomic unit - A categorical aggregation of soils with similar characteristics; a "soil type"; soil mapping units are composed of taxonomic units.

thermic soil temperature regime - A soil temperature regime that has mean annual soil temperatures of 15C or more but less than 22C, and more than 5C difference between mean summer and mean winter soil temperatures at 50 cm.