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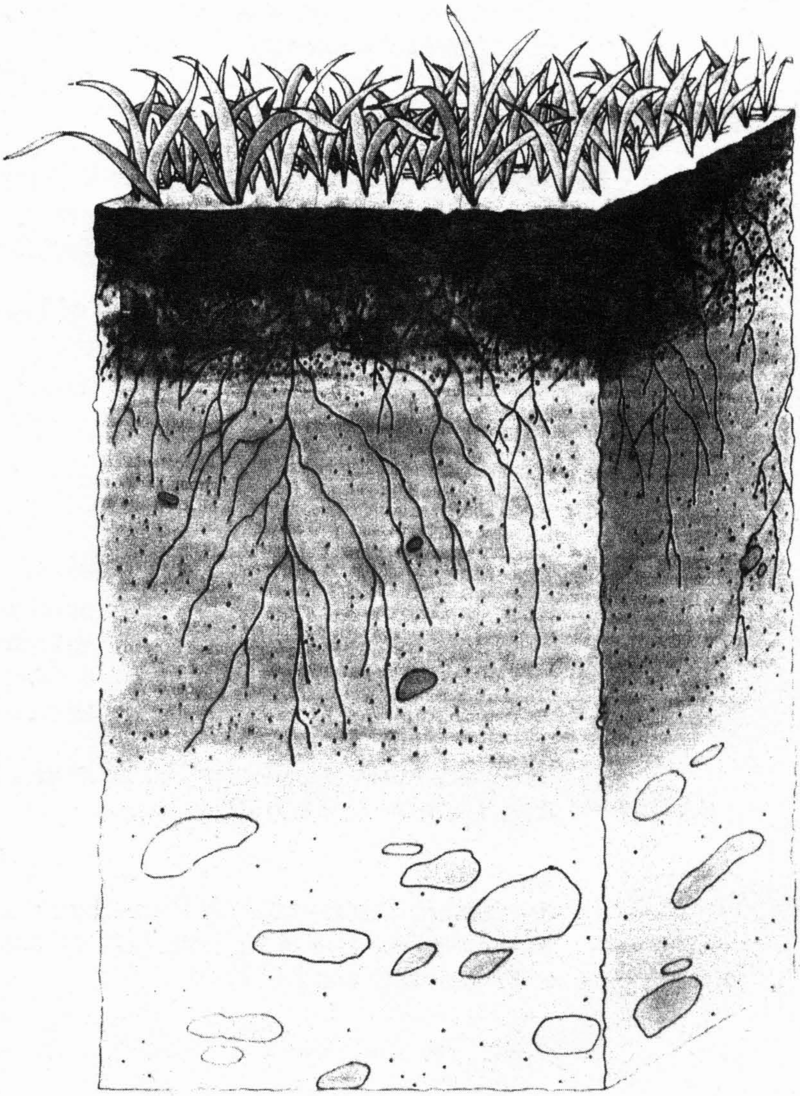

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Organized by:
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Preface

Soil is a nonrenewable resource. It must be maintained in good condition in order to sustain land productivity. Evaluation of the soil parameters that create and maintain sustainable resource use are not yet completely well developed. However, Soil Scientists know that soil characteristics vary in their importance to different land uses and to the part of the world in which they exist. Soil scientists also know that soils vary in their resistance to degradation from various uses.

The purpose, development, evaluation, and application of soil quality standards were addressed in eight papers at the 1990 Soil Science Society of America meeting in San Antonio, Texas. All eight invited papers are included in these proceedings.

The purpose of the 1990 Symposium and these Proceedings, is to open and continue a dialog concerning soil quality standards as an approach to conservation of soil resources and sound land management and to stimulate interest in improved application of soil conservation practices and soils research.

Acknowledgements

We want to thank all the authors and co-authors who presented papers at the Symposium and prepared the papers to make these Proceedings possible. Their dedication to conservation of soil resources is commendable. We also want to thank the National Cooperative Soil Survey Conference for recommending the symposium and the Soil Science Society of America for sponsoring it.

Special thanks go to Earl Alexander for preparing specifications for papers, to Rae Pfeifer for handling and getting the Proceedings organized for printing.

Introduction

Soil scientists are in the midst of an unprecedented concern for man's ability to sustain the earths renewable resources and ecosystem health. Our land use practices are challenged to meet present needs without compromising our capability to meet future needs. A strong demand has been made by the public and land managers for scientifically based data on soil resiliency and relationships of soil characteristics to gains or losses in productivity or hydrologic function. From this, judgements can be made about the effects of management practices on soil productivity.

Many believe that the maintenance of soil quality is the most important requirement for the long term sustainability of the productive capacity on our croplands and forest and range ecosystems. The potential exists, as we all know, for irreversible soil damage. Soil quality standards and thresholds provide early warning signals of impaired soil productivity and help managers prevent permanent impairment to the soil.

These Proceedings mark another step in developing the concept of establishing soil quality standards for physical and chemical soil properties and soil conditions. The idea is not new. Soil erosion T-factors have been around for a long time. In addition, some land management agencies like the Forest Service, have had soil quality thresholds for compaction and other soil parameters for years. These standards have worked fairly well for monitoring and maintaining soil productivity. The existence of standards communicates to the public, that conservationists, foresters, and agrononomists are serious about maintaining the productive capacity of our soils and land base.

The long term sustainability of forests and rangeland and cropland depends on maintaining the quality of soil properties and conditions that affect the productivity and hydrologic functioning of soils. Physical, chemical, and biological characteristics of soils determine soil behavior. Knowledge of these characteristics is essential in making management recommendations that will assure the maintenance of favorable soil conditions and productivity.

The goal of conservation is to sustain output without permanently impairing the productivity of the land. Soil, along with climate, physiography, and biology, set the limits on productivity within a region through the control of nutrients, moisture, and air supplies to plant roots. Therefore, soil condition is a good indicator of the status of land productivity. Changes in soil are measurable and can be used to infer changes in production and hydrologic function.

Proper planning and implementation of management activities, with the clear intent of maintaining soil quality, is the foundation for sustaining the favorable condition and productivity of forest, range, and cropland. Proper planning can minimize adverse affects and even improve soil quality. Improperly planned and implemented management activities can adversely affect soil condition and maintenance of soil productivity. Timber harvesting, cattle grazing, cultivation, and other activities have the possibility to create adverse soil disturbances such as rutting, compaction, erosion, and surface soil displacement. These disturbances, depending on magnitude, can significantly disrupt the soils ability to provide nutrients, moisture, and a friable growth medium for plant roots. Subsequently, plant vigor is reduced resulting in increased susceptibility to insect and diseases and reduced production. In addition, compaction and some surface disturbances reduce rainfall infiltration and increase run off and erosion. The result can be lost topsoil and impaired water quality.

It is always appropriate to look at the scientific data supporting the establishment of standards. More research is needed to validate and help establish soil quality standards.

The papers in these Proceedings review what is being done and present approaches to achieve our nations goal of maintaining soil quality and provide insight on the establishment, use and validation of soil quality standards.

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CURRENT APPLICATION OF SOIL QUALITY STANDARDS

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ABSTRACT

Soil Quality Standards are used as a means to maintain long-term soil productivity on National Forest System Lands. Each Region of the Forest Service has developed, or is developing, standards specific to each region. In the Pacific Southwest Region, these standards are based on threshold values for soil cover, soil porosity and organic matter. Soil quality standards are applied during the planning, implementation and evaluation phases of land management projects. Examples from the Stanislaus National Forest in California are used to demonstrate: 1. How monitoring was used to evaluate the effects of specific management practices on soil properties and conditions; 2. The consideration that is given in project design to meet soil quality standards; and 3. The refinement of land management practices as a result of soil quality monitoring.

CONCEPTS AND FOREST SERVICE DIRECTION

Soil quality standards provide threshold values beyond which further alteration of soil properties would significantly change or impair the productivity potential of the soil.

The term "significant" is used in the context intended by the National Environmental Policy Act, that is: "Important." It is not used in the statistical sense. Significant changes in productivity of the land are indicated by changes in soil properties that are expected to result in a reduced productive potential. Based on available research and current technology, a guideline of 15 percent reduction in inherent soil productivity potential is used as a basis for setting threshold values for measurable or observable soil properties or conditions.

Each region of the Forest Service is required to develop region specific soil quality standards. As a minimum, at least 85 percent of areas impacted by soil disturbing activities will not exceed established threshold values for soil properties or conditions. Individual national forests may further refine these standards as necessary to fit local soil conditions.

STANDARDS IN THE PACIFIC SOUTHWEST REGION

In the Pacific-Southwest Region, which includes the national forests in California, soil quality standards are tied to the key soil properties and conditions of soil cover, soil porosity, and organic matter. These soil properties and conditions are used because they are affected in some way many land management activities, can be easily observed and measured, and can serve as indicators of potential change to other soil properties and conditions.

Thresholds for Soil Properties and Conditions

Soil Cover

Soil Cover is sufficient to prevent accelerated sheet and rill erosion from exceeding the rate of soil formation.

Soil Cover is measured by Toe Point Transects in a stratified random scheme. Effective ground cover may be low growing vegetation, plant litter greater than 2.5 centimeters deep, or rock fragments greater than 2 centimeters in diameter.

The amount of soil cover needed to prevent accelerated sheet and rill erosion from exceeding the rate of soil formation is guided the California Soil Survey Committee's Erosion Hazard Rating System.

Soil Porosity

Soil Porosity is at least 90 percent of its "Natural Condition."

The availability of water, air, and nutrients to plant roots decreases as soil macro porosity decreases. This is especially important in the xeric areas of California where plants rely on stored soil moisture for growth.

A threshold value for change in total soil porosity is used instead of change in soil bulk density because it correlates more directly to potential change in plant growth. Greater increases in soil density can occur on "low" density soils than on "high" density soils before plant growth is significantly affected. Although soil density is the property that is measured, soil porosity is calculated from bulk density to provide a "sliding scale" of allowable bulk density increases. For example, the 10 percent decrease in total soil porosity threshold compares to about a 33 percent increase in bulk density for a soil with an initial density of 0.6 Mg/m^3; about a 16 percent density increase for an initial density of 1.0 Mg/m^3; and a about 9 percent density increase for an initial density of 1.4 Mg/m^3.

Soil bulk density is measured by nuclear guage on stratified random transects and total soil porosity is calculated. At the time of transecting, visual evidence of compaction is observed. If a good correlation between measurements and visual evidence indicators occurs, the more rapid transecting by visual observation is used, with occasional re-checking by measurement.

Organic matter

Thresholds for organic matter fall into three categories.

1. Litter and Duff occurs over about 50 percent of disturbed areas. When present, woody material is mostly less than 7.5 cm in diameter and in contact with the soil surface.
2. Large woody material, in forested areas, quantities are 2 or more logs/ha. Each log is larger than 40 cm in diameter and about 1.5 m^3 in volume.
3. Soil organic matter is at least 85 percent of its natural condition total in the upper 30 cm of the soil.

Organic matter is used to reflect nutrient supply and availability. It serves as a reservoir for short and long-term nutrient supply, and as a habitat for soil organisms which convert nutrients into usable forms for plants. Organic materials can also lessen adverse physical effects such as compaction and soil puddling due to raindrop impact. Large woody material provides hot summer survival habitat for microrganisms, small animals, and insects that convert nutrients into usable forms or spread nitrifying bacteria. Large woody material can be especially important on harsh sites or radically changed sites.

Surface organic matter (litter, duff and large woody material) amounts are determined by transecting. The soil organic matter threshold is used in areas where soil displacement has occurred (mainly due to piling). The amount of soil in piles is calculated and compared to the percentage of organic matter in the top 30 cm of the soil as determined by existing laboratory data.

The 50 percent litter and duff cover is usually the minimum amount of organic matter that is be left on a site (allowances are made for sites which do not have the inherent capability to produce the specified amounts of organic matter). In practice, more surface organic matter may be needed for soil cover to meet erosion control needs.

APPLICATION OF SOIL QUALITY STANDARDS

Soil quality standards apply to areas where vegetative management prescriptions are applied, such as timber harvest areas and range allotments. They are not intended to apply to areas with dedicated uses, such as administrative sites, parts of permanent transportation systems, trails, and special uses. The process of dedicating land to other uses is covered in forest plans or individual resource agency direction.

Soil quality standards are used at three key points:

1. Project Planning
2. Project Implementation, and
3. Project Evaluation.

Soil quality standards are the basis by which proposed land management activities, such as timber harvest, site preparation, reforestation, and wildlife habitat improvement projects are evaluated for soil related concerns in the environmental analysis process. Site specific project areas are evaluated to determine how existing soil conditions compare to soil quality thresholds, and how the planned activity might affect meeting the soil quality standards. It is noted whether the project as proposed, meets or does not meet the soil quality standards. In the case of the proposed project not meeting the standards, recommendation for project modification or mitigation are then made, and the modified project is re-evaluated.

Specific examples of applying soil quality standards

On the Groveland Ranger District of the Stanislaus National Forest in California, most timber harvest and mechanical site preparation project proposals have soil compaction, soil erosion, and soil displacement identified as concerns during the project analysis process. It should be noted that the Groveland Ranger District ranks is in the top five percent nationally of number and size of catasrophic wildfires based on a fifty year average. So all management activities are looked at closely from a fuel management standpoint. This can have an effect on applying the organic matter soil quality standards.

The soil compaction concern rests primarily with ground based heavy equipment trafficking activity areas and how it might affect soil porosity.

The soil erosion concern centers on reduction of ground cover density and reduced infiltration rates on compacted areas. And the displacement concern relates to the use of heavy equipment on steep slopes and brush clearing as it affects soil organic matter content and compaction.

Detailed monitoring was conducted a number of years ago to determine the status of compaction, ground cover, and displacement levels for specific activities such as, log skidding with rubber-tired skidders, bulldozer piling of brush, and bulldozer crushing of brush on various soils. In the case of compaction monitoring, both the degree of compaction and the spatial distribution of compaction were monitored. This monitoring showed logging activities with rubber-tired skidding equipment on soils derived from granitic rock resulted in soil porosity decreases beyond the threshold after about three passes of the equipment.

On soils derived from metasedimentary rock more than five passes of the equipment were necessary to result in soil porosity decreases beyond the Threshold. This was under dry soil conditions. What this meant was that main skidtrails and roads were highly compacted. Less trafficked skidtrails were also compacted, but not beyond the threshold. Depending upon the timber volume to be harvested, topography, and the type of equipment used, main skidtrails and landings made up about ten to twenty five percent of an area.

Site preparation by bulldozer piling of brush resulted in porosity decreases beyond the standard adjacent to piles due to the repeated passes of equipment over these locations, and made up as much as thirty percent of the activity area. Site preparation by ground based biomass harvest resulted in thirty to sixty percent of the area with porosity decreases beyond the standard, depending upon the type of equipment used. This type of monitoring was the basis of the values now being used to analyze potential projects for "expected change" in soil quality parameters during project environmental analyses.

Monitoring also revealed that ground cover amounts following bulldozer brush piling typically resulted in extremely low ground cover. Monitoring also showed that many tons of topsoil per hectare were ending up in bulldozer created brush piles, which was both a soil displacement concern from a productivity standpoint, and a problem for fuel managers who had a hard time burning brush piles that were full of soil.

Monitoring also showed that brush crushing by bulldozer could result in little or no compaction and one hundred percent ground cover if enough brush was on site to begin with. Informal observations by foresters, silviculturists, and fire management officers revealed that most bulldozer piling operators were over achievers in terms of how much brush they were getting into the piles compared to fuel management and plantable site objectives, and that the difference between what was needed, and the "clean" job that was being done was both time consuming and required many additional passes of the equipment.

At the same time, brush crushing was resulting in acceptable fuel loading due to being a close-to-the-ground, tightly-packed brush arrangement after the bulldozer had completed its work.

Equipped with these formal and informal monitoring results, and the soil quality standards, management was in a position to dramatically improve the quality of project proposal environmental analyses, and to ensure that soil productivity was being maintained by tailoring practices to the site. Not only did monitoring provide a means to adjust management practices so that soil quality standards could be met in future projects (project tractor piling specifications were modified to ensure ground cover objectives could be met), but it also identified areas in need of restoration.

During project planning, interdisciplinary teams (with public input) identify issues, concerns, and opportunities related to a proposed project, identify alternative methods for implementing the project, and analyze in detail environmental consequences of proposed activities. Measures are identified to ensure that adverse impacts are avoided, minimized or mitigated.

Soil quality maintenance and implementation methods are incorporated into timber sale, site preparation, and other contract clauses to ensure their application as prescribed. Contract administrators provide one level of soil quality standard monitoring by assuring that all contract clauses are enforced throughout the project areas.

In an example of a timbe sale contract, five downed logs per hectare, which are considered "cull" for lumber production, may be required to be left using a specific contract clause, rather than being pulled out of the harvest unit and used for fuel wood. Logging slash, the tops and branches of harvested trees, can be required to be "lopped and scattered" to forty six centimeters by loggers... meeting both soil cover and litter/duff standards.

In the case of site preparation for planting and fuel reduction, methods such as tractor piling are being replaced by less compacting, less organic matter depleting methods such as crushing, shredding, or biomass removal of small trees not suited for lumber milling, and using them for chips for wood fired co-generation electrical plants. On steeper lands where broadcast burning traditionally was used for site preparation and fuel reduction, helicopter biomass harvest is providing a variety of resource benefits, in addition to meeting organic matter and soil cover standards.

Some management activities may not be able to meet soil quality standards and need to have corrective measures built into them. This can be especially be the case when the cumulative effects of past activities have affected present soil conditions. Natural events also influence the ability to meet soil quality standards. In such cases, corrective measures are implemented whether it is aerial grass seeding or straw mulching to rapidly create soil cover, to prevent erosion, or deep tillage to break-up compacted layers resulting from multiple activities in an area over time.

Another step occurs after a project is completed. That is, monitoring to evaluate if soil quality objectives have been met. The results then can be used for subsequent project analysis refinement. This monitoring also helps close the loop for land managers and line officers, who are generally not soil specialists.

Soil quality standards are taken very seriously by national forest land managers, and are used extensively in the formulation of project proposals and follow-up evaluations.

THRESHOLDS FOR SOIL REMOVAL FOR MAINTAINING CROPLAND PRODUCTIVITY

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During the preparation of the 1977 report for the Soil, Water and Related Resources Act (RCA) it was apparent that information concerning the relationship between the amount of erosion and cropland productivity was inadequate. In the reports (USDA, 1981), erosion was estimated by using the Universal Soil Loss Equation and the estimated erosion amounts were compared with T (tolerance) values (Wischmeier and Smith, 1978). It was concluded that erosion amounts greater than T were excessive. While Wischmeier and Smith (1978) defined T as "the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely, the scientific basis for the choice of T values is obscure (Johnson, 1987).

In 1983, Larson et al. (1983) proposed that the effects of erosion could be separated into irreplaceable and replaceable soil attributes. Irreplaceable attributes include water holding capacity and rooting depth, and replaceable attributes include plant nutrients and organic matter.

Irreplaceable Attributes

Kiniry et al. (1983) developed the following equation to estimate the suitability of a soil as a rooting medium:

$$PI = \Sigma_{0}^{r} (A*B*C*D*E*WF) \qquad [1]$$

where

A = sufficiency of available water capacity
B = sufficiency of aeration
C = sufficiency of bulk density
D = sufficiency of pH
E = sufficiency of electrical conductivity
WF = weighting factor based on an idealized root distribution with depth
PI = productivity of soil environment
r = number of horizons in depth of rooting under ideal conditions.

The parameters in the equation are expressed as a sufficiency index. The indexes are multiplicative for each soil horizon and summed so that the productivity index (PI) varies from 0 to 1.0, with 1.0 having the greatest productivity. For application to the Cornbelt, Pierce et al. (1984a) used only the parameters A, C, D, and WF. The soil horizons were weighted by depth according to an idealized root distribution using a total depth of 1.0 m. Further it was assumed that through management C and D were made equal to 1.0 in the surface 20 cm of the soil. To estimate the losses in productivity from erosion PI was calculated using data in the SOILS-5 database[1/] for the locations given in the NRI[2/]. PI was progressively calculated following removal of 2 cm increments from the surface soil and adding an equal amount of soil below the 100 cm depth. Pierce et al.'s (1983) use of equation 1 estimated the losses from nonreplaceable attributes.

Figure 1 shows PI plotted vs. cm of soil eroded for three Midwest soils. The Port Byron is a Typic Hapludoll developed from loess, with loamy textures to 150 cm or more. The Kenyon is a Typic Hapludoll with medium surface textures and firm till in the subsoil. The Rocton is a Typic Argiudoll of medium texture to about 70 cm over consolidated materials. Note that the that the irreplaceable attributes in the Port Byron soil are not damaged seriously by

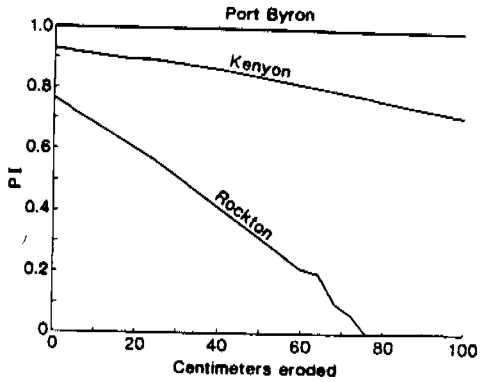

Fig. 1. Productivity index (PI) plotted against centimeters of soil removed. The average slopes (x 100) for the Port Byron, Kenyon, and Rockton soils are 0. -0.2, and -0.8, respectively, and they reflect the vulnerability (V) of the soils to the loss of nonreplaceable attributes.

[1/] Soil Conservation Service, the SOILS-5 database (unpublished).

[2/] Soil Conservation Service, National Resource Inventory of 1977 (unpublished) line is nearly flat. The irreplaceable attributes immediately below the 100 cm depth are approximately as favorable as those on the surface. In contrast, in the Kenyon and Rocton, PI decreases as erosion progresses because of high bulk densities or consolidated material below the A horizon.

Pierce et al. (1984) defined the slope of the lines in Figure 1 as the vulnerability, V, of a soil to erosion damage. The V is defined as

$$V = (\Delta PI/\Delta d) * 100 \qquad [2]$$

where Δd is the difference in soil depth, taken arbitrarily as -50 cm. For the Port Byron soil, V = 0, for the Kenyon soil, V = -0.2, and for the Rocton, V = -0.8.

Both PI and V vary for soils in a Major Land Resource Area (MLRA) (USDA,1981). Figure 2 shows a frequency distribution of PI for MLRA 98 in southern and central Michigan.

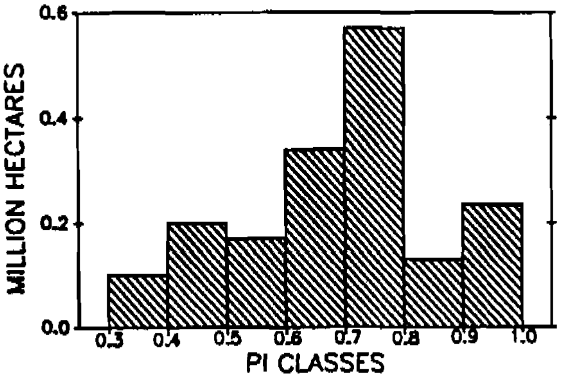

Fig. 2. Distribution of PI classes versus hectares of cropland in Major Land Resource Area 98 in Michigan.

Note that the PIs vary from 0.3 to 1.0. We suggest that a PI of 0.5 is the threshold below which a soil cannot be economically cropped to the common deep-rooted field crops unless amended with irrigation or drainage. Pierce et al. (1984b) showed that PI is roughly linearly related to corn and cereal yields in a number of MLRAs. The average corn (Zea mays L.) yield in the 1985-1989 period for the USA was 7000 kg ha^{-1}. Thus, if a PI of 1.0 equals 7000 kg ha^{-1}, a PI of 0.5 is approximately equal to 3500 kg ha^{-1}. Obviously, a PI threshold will depend on many costs of production so that a PI of 0.5 is only a general threshold estimate. About 17% of the cropland area in MLRA 98 has PIs less than 0.5.

Figure 3 shows the V distribution for MLRA 98. Again, quantitative data are lacking but our estimation is that any soil with a V of less than -0.6 is so fragile that it should not be cultivated to ordinary field crops because of potential serious damage from erosion. Twelve percent of the cropland soils in MLRA 98 has V value of -0.6 or less. A V value of -0.6 might be considered a threshold.

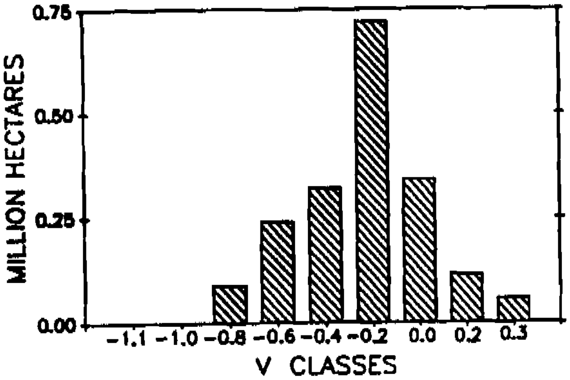

Fig. 3. Distribution of Vulnurability (V) classes in Major Land Resource Area 98 in Michigan.

From the foregoing, Roloff et al. (1988) defined a resistivity index (RI). It is defined as

$$RI = 1 - (E/E_m) * (V/V_m) \qquad [3]$$

where E = RKLS from the Universal Soil Loss Equation (Wischmeier and Smith, 1978);

E_m = the maximum RKLS in the area of study

V = vulnerability (equation 2)

V_m = maximum vulnerability in the area of study

RI varies from 0 to 1.0.

Using the PI index and the RI index Larson et al. (1988) constructed the two-dimensional diagram shown in Figure 4. They suggested that the soil mapping units in a county may be divided into 4 quadrants and proposed that the quadrants could define quality of lands for government programs. Note the upper right designates resistant, productive soils where crop production should be encouraged because of efficiency of production without potential damage from erosion. The upper left defines non-resistant, productive soils - suitable for set aside lands for commodity production controls. The soils are productive but are sensitive to damage. The lower left represents non-resistant non-productive soils that are suitable for CRP or long-term

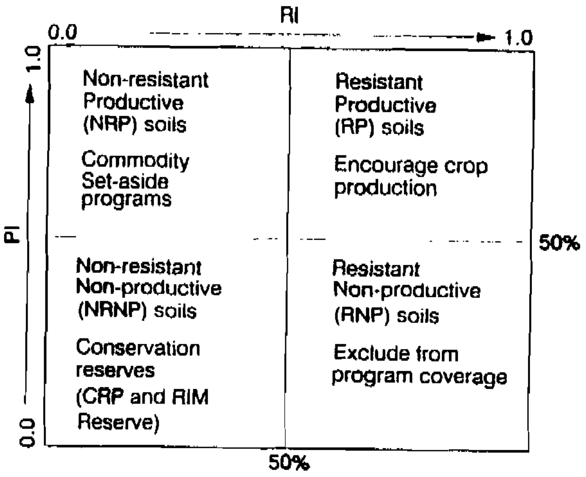

Fig. 4. Land associated with soil conservation and farm programs.

set-asides. The soils in the lower right are resistant but non-productive. These should be excluded from government programs because they are not likely to be damaged. Eventually, economic forces will force them out of crop production. This general scheme of designating lands has been used in a Minnesota program called RIM (Reinvest in Minnesota) which is similar to CRP (Conservation Resource Program) (Larson et al., 1988). The size of the four quadrants in Figure 4 can be adjusted to provide a pool of land of any desired size. In the Minnesota RIM program only land with a PI and RI of less than 0.25 was used for selection (Larson et al., 1988).

Replaceable Attributes

Replaceable soil attributes are those that can be replaced, although at a cost. Of these, perhaps organic carbon (OC) is most important. Larson et al. (1972) added a variety of organic residues at various rates to a Typic Hapludoll in western Iowa (MLRA 107) for 11 years while cropping the soil to corn (Zea mays L.) with moldboard plowing. At the end of the 11 years, OC varied linearly with amount of residues added as shown in Figure 5. Rasmussen and Collins (1991) have shown a similar linear relationship for the Palouse area of Oregon and Washington.

From these linear equations we calculated the annual amount of residue for return to the soil that was required to maintain the OC at the level present at the start of the experiment (Iowa, 1.8) and this is shown in Column 3, Table 1. Then we calculated the average amount of OC in the residues produced from corn (Zea mays L.) in MLRA 107 (Iowa and Missouri deep loess

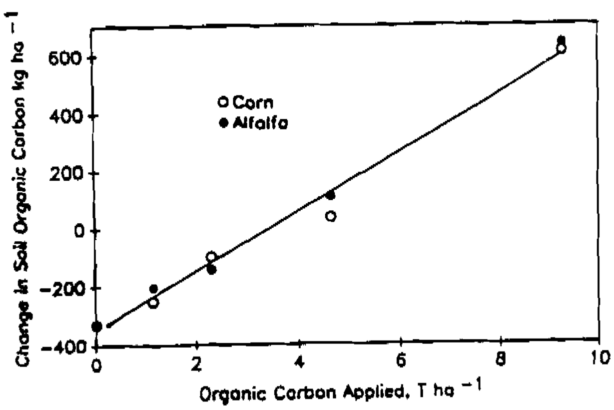

Fig. 5. Effect of annual addition of crop residues on change in soil organic carbon.

hills)) and from wheat (Triticum aestivum L.) in MLRA 9 (Palouse and Nez Perce Prairies) in Washington and Oregon. We assumed a harvest ratio of 1.0 for corn and 1.5 from wheat (Column 4), and used average grain yields for the MLRA's in 1988. In Column 5, we give the ratio of the OC required to that produced. In the corn and wheat-fallow (w-f) rotation, the ratio is 0.8 or 0.9. In the continuous wheat, the ratio is 3.9. Because OC changes in the soil are difficult to measure, we propose that the ratio is a useful index of whether OC is increasing or decreasing for soils in a given MLRA.

Erosion removes OC in the sediments. In Table 2 we have calculated the OC in average erosion rates by slope class for MLRA 107 and then calculated how much residue it would require to maintain the soil at 1.8%. Note that on the steeper slopes the amount of residues required far exceeds that produced by corn or other grain crops. Hence, it is obvious that on the steeper slopes where erosion is severe, OC will decline to low levels.

SUMMARY

Many properties of the soil are changed as a result of soil erosion. They can be divided into irreplaceable and replaceable attributes. Irreplaceable attributes include water-holding capacity and rooting depth, while replaceable includes plant nutrients and organic matter.

Methods for estimating the potential productivity (PI) and the vulnerability (V) of the soil to damage from erosion are outlined. Threshold values of PI and V for cropland soils are suggested. The vulnerability to damage and the potential for erosion occurrence are combined in a Resistivity Index (RI). A two-dimensional graph using PI and RI are suggested as a means to designate lands for government set-aside programs.

A means to estimate whether the organic matter content of a soil will increase or decrease based on the amount of organic residues returned to the soil is suggested.

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Table 1. Amounts of organic carbon additions necessary to maintain the soil organic carbon at present levels at several locations.

Location	Crop Rotation[1]	Amount of Organic C to maintain soil O C	Amount of Organic C produced from crops	Ratio
		kg/ha/yr		
Shenandoah, IA	c-c	3272	3020	0.9
Pendleton, OR	w-f	2288	1764	0.8
Pullman, WA	w-f	1933	1764	0.9
Pullman, WA	w-w	780	3528	3.9

[1] c = corn, w = wheat, f = fallow.

Table 2. Amounts of organic carbon needed annually in residues to maintain soil organic carbon on different slopes and erosion levels in Major Land Resource Area 107.

Hectares (1000)	Slope %	Avg. Erosion[1] t/ha-yr	Organic C in sediment[2] kg/ha	Organic C needed in residue
853	0-2	5	135	1900
1157	2-6	18	486	6840
819	6-12	61	1647	23180
376	12-20	114	3078	43320

[1] From Soil Conservation Service, National Resource Inventory of 1977 (unpublished).

[2] Enrichment ratio of 1.5, organic carbon in soil = 1.8%.

SOIL LOSS TOLERANCE AS RELATED TO RANGELAND PRODUCTIVITY

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ABSTRACT

Rangelands are important natural ecosystems that occupy about 40% of the world's land area. They occur in widely different geographic and climatic environments and, as a result, display a wide range of resiliencies to grazing and other uses. The inherent resiliency to use reflects a dynamic interaction between erosion and soil formation processes and plays an important role in the long-term productivity of rangelands. Past overgrazing and other misuse have caused extensive erosion on many western rangelands, which has led to an irreversible loss in site productivity. As a result of this disturbance, these sites support a lower successional stage of vegetation than when occupied by climax species prior to settlement. This paper discusses soil loss tolerances within the concept of a dynamic balance between soil loss and formation. It also examines some of the different rehabilitation strategies within the context of soil loss tolerances. Based on our present level of understanding of rangeland soils, T values for rangelands will probably remain subjective within the general conceptual framework of erosion losses and soil formation.

INTRODUCTION

An important resource throughout the world is rangelands, which occupy about 40% of the earth's land surface (Branson et al., 1981). In the United States 38%, or 347 M ha, of the total land area is classified as rangeland (Wight and Siddoway, 1982). Rangelands include natural grasslands, open interspaces in woodlands (e.g., pinyon-juniper and oak), savannas, shrublands, some deserts, tundra, alpine communities, coastal marshes, and wet meadows (Kothmann, 1974). Currently, riparian areas occupying the more mesic riverine sites are considered an integral part of the overall management of this resource (Renard et al., 1985; DeBano and Schmidt, 1989).

A wide range in past use, and misuse, of rangelands has occurred. Rangeland abuse and associated accelerated erosion has occurred worldwide, and Lowdermilk (1975) attributed the downfall of several ancient civilizations to soil erosion and siltation problems resulting from mismanagement of the soil resource, primarily on rangelands. Historic abuse of western rangelands is also well documented (Buffington and Herbel, 1965;

Box, 1979; Renard et al., 1985). Overgrazing is considered one of the most important factors intensifying desertification in arid and semiarid environments (Dregne, 1978). Overgrazing is especially devastating when rangelands are undergoing drought stress (Renard et al., 1985).

Rangelands can be found under a wide range of temperature and moisture regimes, ranging from desert environments to alpine tundra, although the majority of the rangelands exist under arid climates. Precipitation ranges widely, with some grasslands receiving less than 25 cm of precipitation and tropical savannas receiving 300 cm or more annually. Low precipitation is further complicated by large temporal and spatial variability (Renard et al., 1985). In many cases, the total annual precipitation may occur during a few months as high-intensity rainstorms, leading to frequent droughts.

The inherent productivity of rangelands in the United States varies widely from highly productive, climax, tall grass prairies to stressed, desert grasslands undergoing desertification, depending, to a large extent, upon climate, soil depth, and past use. In general, the more productive rangeland soils are deeper and are found in areas of higher precipitation, whereas shallower younger soils in arid climates are less productive. For example, the deep fertile soils of tall grass prairies can produce 3,300 kg ha^{-1} of forage per ha (Stoddart et al., 1975). Desert soils represent the extreme end of the spectrum and may support only a sparse plant cover because they receive little precipitation and are exposed to long periods of high temperatures. Rangeland soils found in the more arid climates also frequently have restrictive soil horizons (e.g., calic, natric, gypsic, and salic horizons or duripans or petrocalcic horizons) or excessive concentrations of soluble salts (saline and alkali soils).

Generally, because they typically occupy steep rocky hillsides, the physical conditions on many rangeland sites are more restrictive for luxuriant plant growth than they are on croplands. It has been estimated that about 71% of the rangelands in the United States have slopes exceeding 12%, as compared to only 10% for cropland (Wight and Siddoway, 1982). Because a large proportion of rangelands are found on fragile soils having steep slopes under harsh environments, productivity is limited and their resiliency to use may be low. As a result, soil loss by erosion becomes an important consideration when one manages rangelands. Erosion rates on rangelands vary widely, depending upon climate, vegetation, topographic features, and human activities. Therefore, there is an urgent need to better quantify the interrelationships between soil productivity and soil erosion in order to provide a sounder basis for establishing tolerable soil loss standards for rangelands.

The objectives of this paper are to (1) review the general concept of soil loss tolerance, (2) examine some of the assumptions underlying soil formation and erosion losses, (3) indicate some current on-the-ground attempts being made to establish soil tolerance values for rangelands, (4) outline some obstacles encountered when implementing soil T values on rangelands, and (5) discuss some general rehabilitation strategies for improving soil productivity.

SOIL LOSS TOLERANCES

Historical Perspective

Soil loss tolerance or "T value" was first defined as "the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely" (Wischmeier and Smith, 1978).

Soil T values were initially developed to establish tolerable soil losses from croplands, but were later extended to rangelands (Wight and Lovely, 1982) and forests (Alexander, 1988a). It is important to distinguish between soil T values and soil loss limits (Hall et al., 1985). Soil T values deal solely with maintaining vegetative (agricultural crops, trees, and grasses) productivity, whereas soil loss limits also address reducing sediment losses from watersheds (Moldenhauer, 1982). However, soil T values are difficult to apply for water quality purposes, because they do not reflect channel erosion processes (Wight and Siddoway, 1982).

Soil T values are a useful concept when one is dealing with soil productivity on rangelands. Soil productivity is defined as the capacity of a soil, in its normal environment, for producing a specific plant or sequence of plants under a specific management system (Williams, 1982). In forestry, it has been defined as a soil's ability to support and produce biomass where the maximum potential production is a function of both extrinsic and intrinsic site factors (Klock, 1983). Extrinsic factors are those over which the ecosystem has no marked influence; they include soil parent material, topography, and regional climate. Intrinsic factors are those influenced by the presence of the ecosystem and processes occurring within the ecosystem; they include a range of soil-forming processes (i.e., nutrient cycling). In arid environments, as is commonly found on rangelands, water availability may be a key environmental factor limiting productivity (Hadley and Szarek, 1981). Primary productivity in desert ecosystems can also be limited by nutrient availability (especially nitrogen) and species productive potential.

Procedures for Determining Soil T Values

Soil loss T-values have been established by two general procedures: one is based on the concept of maintaining sustained productivity of a site and the other, on the rate of soil formation. The T values required for sustained productivity have been derived mainly from experiments conducted on crop yield responses to incremental soil removal or loss; these have limited utility for establishing T values for rangelands. Few data on plant responses to erosion losses are available for rangelands. On the other hand, acceptable levels of soil loss can theoretically be based on a steady-state balance between the rates of soil denudation and soil formation. In practical terms, no more soil can be lost by erosion than is formed. A major obstacle when these concepts are applied to rangelands is the difficulty of quantifying soil loss and formation rates. The relationship between soil productivity and soil losses is further complicated by the resiliency of site productivity to the intensity of erosion on different areas.

SOIL LOSS AND FORMATION

Denudation and Erosion rates

Denudation and erosion rates have been measured in a wide range of environments, extending from continental estimates reported by geomorphologists to those measured on small plots by agronomists and engineers. As a result, the specific erosion rates reported in the literature vary widely, not only because of inherent differences in erosion rates but also because of measurement scale.

Large-Scale Denudation

Rates of denudation for the entire United States have been estimated to be about 60 mm per 1,000 yr (Judson and Ritter, 1964). This average reflects a wide range of values, although for smaller drainage basins, the denudation rates can be on the order of several centimeters per year, with average maximum denudation rates of 1 mm yr^{-1} (Schumm, 1963). These estimates include stream channel and bank erosion, in addition to surface soil erosion on hillslopes.

Erosion rates are affected by a large number of factors, including rock type, relief, and climate. A study of the relationship between natural rates of erosion and precipitation for continental climates revealed that maximum natural erosion rates for small drainage basins (between 26 and 130 km^2) occur in semiarid regions (Langbein and Schumm, 1958). Large-scale estimates of combined water and wind erosion from nonfederal rangelands in the West range from 4.2 to 11.2 t ha^{-1} or about 0.3 or 0.4 to 1.0 mm yr^{-1} (Wight and Siddoway, 1982).

A generalized curve relating erosion to precipitation, but largely dependent on vegetation, was developed by Schumm and Harvey (1982) (Fig. 1). This relationship is based on the assumption that under humid climates vegetation protects the soil, but in arid regions there is insufficient rainfall and runoff to move large quantities of sediment. Therefore, erosion rates are greatest at intermediate rates of precipitation where vegetation protection is low, yet there is sufficient rainfall and runoff energies created to move large quantities of sediment out of the drainage basin (Schumm and Harvey, 1982). It is postulated that when the natural

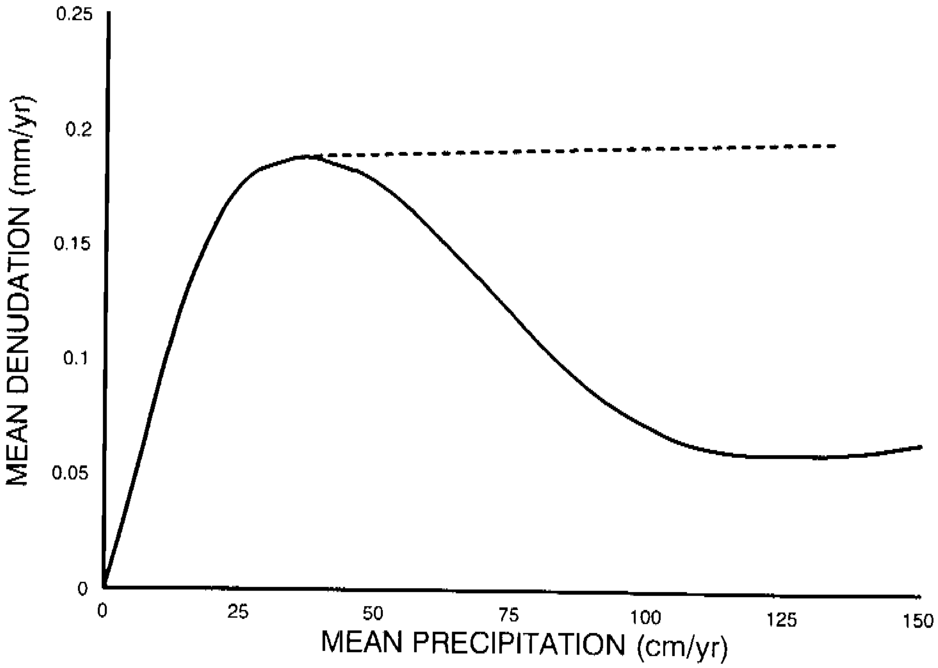

Figure 1. Natural denudation rates with precipitation (After Schumm and Harvey, 1982). The dashed line represents a high sustained level of erosion, resulting from the destruction of climax vegetation cover.

climax grassland vegetation is removed, either by cultivation or overgrazing, then erosion rates are increased not only under semiarid conditions but even more so on areas receiving higher amounts of annual precipitation (dashed line in Fig. 1). The form of the dotted line is not known, although substantial increases in erosion would be expected to result from the denudation of climax vegetation in high precipitation areas. In the United States, the lower precipitation areas would be represented by the desert grasslands and the intermediate precipitation by the tall grass prairies.

Erosion Rates on Small Areas

Erosion rates based on data from plots and small watersheds are more sensitive to human activities, because these rates are usually measured during site-specific studies and reflect individual management practices. Although soil loss is difficult to measure, rainfall simulation and small-gaged watersheds provide opportunities for measuring actual soil loss from specific sites. Soil loss measurements from small plots, however, may not be directly comparable to watershed measurements, particularly on a short-term basis, because of the storage and episodic transport of sediment in response to large storms (Wolman, 1977). Therefore, small plot data should be used primarily for indexing soil parameters, precipitation, and specific management activities, which can be used as input data for predictive equations for hillslope processes.

The Universal Soil Loss Equation (USLE) is an example of a model that has been used extensively in the past for predicting erosion from croplands and rangelands. More recently, a cooperative Water Erosion Prediction Project (WEPP) by the Agricultural Research Service (ARS), Forest Service (FS), and the Bureau of Land Management (BLM) has been implemented to develop an improved model based on modern technology for estimating soil erosion by water. This WEPP technology is based on fundamental hydrologic and soil erosion processes and is designed to replace the widely used Universal Soil Loss Equation (USLE). The refinement of these models, potentially, will provide a more accurate tool for predicting onsite hillslope erosion rates and eliminate the need to depend upon generalized estimates based on a continental scale.

Soil Formation Rates

To base soil T values on a steady-state balance between soil formation and losses, one must have reliable estimates, or predictions, of soil formation rates (Alexander, 1988a). Estimates of soil formation have been based on two different types of data, namely the rates of (1) soil organic matter (OM) accumulation and soil horizon differentiation (Hall et al., 1982), and (2) soil formation from lithic and paralithic materials (Alexander, 1985, 1988a).

Horizon Differentiation

The incorporation of OM in the surface of parent material is usually considered to be the first indication of soil formation and the formation of a mollic epipedon and can require between 24 and 200 yr, depending upon climate, vegetation, type of parent material, landscape position, and topography (Schumm and Harvey, 1982). However, the development of a true mollic horizon can require from 200 to 3,000 yr (Birkeland, 1974). This is compared to the 8,000 yr Franzmeier and Whiteside (1963) estimated it took a Spodosol to form.

Studies under grass on alluvial floodplains (Parsons et al., 1970; Ruhe et al., 1975) showed that Mollisols, or soils approaching Mollisols in OM accumulation, could form in 100 to 120 yr. It is generally concluded that OM can accumulate very rapidly under grass vegetation, and a steady state between gains and losses can be reached in a few hundred years (Hall et al., 1982).

Kohnke and Bertrand (1959) found that the total amount of soil formed was a function of both age and soil depth. For example, the upper 25 mm of soil may form in as little as 50 yr (0.5 mm yr^{-1}), but a soil having a depth of 2.5 m may require 150,000 yr (0.02 mm yr^{-1}) to form an additional 25 mm of soil depth. Pimental et al. (1976) considered that under ideal soil management conditions 25 mm of soil can form in 30 yr (0.8 mm yr^{-1}) (Schumm and Harvey, 1982).

Other forms of horizon differentiation than those associated with OM accumulation can influence productivity and must be considered when developing soil T values. These include the translocation and accumulation of clay to form argillic horizons. Equally important in arid environments is the formation of calic, natric, salic, and petrocalcic horizons.

Soil Formation from Lithic and Paralithic Materials

Estimates on the rates of soil formation from consolidated materials have become available primarily during the last 25 yr (Alexander, 1988a). Earlier estimates by Trimble (1963) indicate that about one million years were required for the development of a deeply weathered Ultisol in northwestern Oregon. A recent comprehensive analysis of the data from 18 watersheds indicates that the rate of soil formation on noncarbonate lithologies can range from 0.02 to 1.9 Mg ha^{-1} yr^{-1} (Alexander, 1988a). These rates of soil formation were dependent upon the volume of runoff water and the soil-to-rock ratio. Therefore, the maximum rate of soil formation from lithic materials is only about 0.16 mm yr^{-1} (assuming a bulk density of 1.20 g cm^{-3}).

Soil Formation and Productivity

Both horizon differentiation and rock weathering rates affect soil productivity and both must be considered when developing soil T values. Horizon differentiation processes, particularly those responsible for mollic and umbric epipedon development, affect both the long- and short-term soil productivity because carbon and nitrogen cycling and accumulation are involved in these processes. Although the chemical weathering of lithic and paralithic materials is less subtle, this process controls the long-term replenishment of the soil mantle with cations and other nutrients essential for plant growth.

The incorporation of OM into the soil surface is an important process affecting the sustained productivity of rangeland soils. Soil OM acts as the primary reservoir for several nutrients and, therefore, is the source for most of the available phosphorus (P) and sulfur (S) and, virtually, all of the available nitrogen (N). Soil OM's role in N storage is especially important in rangeland soils because their continued productivity depends, to a large extent, on a supply of available N. Partially decomposed soil OM and humus also provide chemically active cation exchange sites that retain many of the important cations (e.g., NH_4^+, K^+, Ca^{++}) and reduce onsite leaching losses. Organic matter serves as a powerful aggregating agent and, as such, plays an important role in creating and maintaining a well-aggregated soil. Soil aggregation improves soil structure, creating macro pore space, and improves soil aeration. As a result, aggregated soils also have higher infiltration rates than nonaggregated soils containing less OM.

Plant productivity also depends on soil, climate, management, plant varieties, weather, pests, and diseases. Management includes cultivation, plant distribution, fertilization, irrigation, and control of pests and diseases. As a result, productivity may not be a single value for each soil but may have different values for a wide array of plant species. However, on rangelands, less opportunities are available for fertilizing, irrigating, cultivating, and selecting a wide range of different plant species.

DEVELOPING AND IMPLEMENTING SOIL T VALUES ON RANGELANDS

Several obstacles that arise when attempting to develop T values for rangelands are: (1) inadequate inventory and research information on rangeland soils; (2) difficulties in quantifying soil erosion rates, particularly, separating geologic from that caused by human activities; (3) lack of information on the resiliency of soil productivity to erosional processes; (4) highly variable climate, both temporal and spatial; and (5) shallow soils.

Available Information on Rangeland Soils

Surprisingly, little effort has been directed toward summarizing and synthesizing the existing information on rangeland soils. To this author's knowledge, a basic soil textbook on rangeland soils does not exist. In contrast, there are numerous textbooks on agricultural soils and a few describing forest soils. No attempt has been made to bring together and synthesize a state-of-the-art text on range soils. Consequently, the available information on rangeland soils is widely dispersed throughout the published literature and has not been synthesized into a compendium.

Although information on cropland soils serves as a starting point, there are several obvious characteristics affecting productivity and tolerable soil losses that separate rangelands from croplands. These are: (1) differences in total nutrient pools, (2) variable and unpredictable climate on rangelands, (3) management and uses, and (4) steeper slopes.

Soils T Values for Crop and Rangelands

Select published data on rates of soil formation and plant productivity responses to erosion indicate that tolerable soil losses vary widely for croplands (Table 1). Generally, the T values for croplands range between 7 and 11 t ha^{-1} yr^{-1}. Data for rangelands are essentially nonexistent, although T values or 4.5 t ha^{-1} yr^{-1} were proposed by Wischmeier and Smith (1978) after compensating for shallow soils on rangeland sites. Recent data on rates of soil formation from consolidated parent material supporting grasslands show it to be slow indeed (Table 1). For example, Alexander (1988a) calculated that the rates of soil formation under grassland vegetation may be 0.33 t ha^{-1} yr^{-1} or less.

Estimating Soil Erosion Rates

The relationship between soil erosion and productivity is further complicated by the difficulty of determining current erosion rates. Erosion can be a slow and insidious process that is difficult to evaluate in terms of biomass production. The difficultly of detecting erosion is also

Table 1. Soil tolerance values for crop and rangelands.

Losses (mt ha^{-1})	Experimental basis	Cover type	Source
6.7	Plant response	Cropland	Hays and Clark, 1941
9	" "	Cropland	Smith, 1941
7-11	" "	Cropland	Browning et al., 1947
2-4	" "	Cropland	Smith et al., 1948
8-9	" "	Cropland	Van Doren and Bartelli, 1956
4.5	Plant response[a]	Rangeland	Wischmeier and Smith, 1978
.03	Soil formation	Grassland	Alexander, 1988a
.20	Soil formation	Savannah	Alexander, 1988a
.33	Soil formation	Pasture	Alexander, 1988a
1.72	Soil formation	Moorland	Alexander, 1988a

[a] Based on plant response for croplands that was reduced to compensate for shallow soils found under grasslands.

compounded by the nonlinear nature of the erosion process (Williams, 1982). Techniques available for determining and predicting erosion rates are currently available in a user handbook on rangeland hydrology (Branson et al., 1981)

Estimating erosion rates is further complicated because current rates of erosion reflect not only natural rates of erosion but also those produced by a multitude of past and present management activities. Natural losses are those that could be expected under climax vegetation and should be estimated on areas containing such vegetation. Unfortunately, such areas are difficult to locate. Although some exclosures and relic areas have been set aside, these areas usually either have remnants of past use or are influenced by the use occurring on nearby areas. As a result, most of these areas do not provide adequate baseline information for establishing natural erosion rates. For example, it is difficult to find suitable exclosure study areas, because the areas have either not reverted to climax vegetation (low resiliency), or rodents from nearby used areas have concentrated and severely disturbed the soil and vegetation.

Soil Productivity Resiliency

Another hurdle encountered when dealing with the erosion-productivity concept is the difficulty of restoring the productivity of fragile soils, particularly on severely disturbed rangelands in arid climates. Erosion in many arid areas has already proceeded to a level where it is impossible, both physically and economically, to restore the original soil-vegetation to a climax state. This usually occurs when a catastrophe (either natural or human-caused) reduces vegetation cover beyond some critical point, so that erosion is accelerated to the point that the entire soil mantle is lost. Once an accelerated erosion cycle begins, it often becomes self-sustaining. These erosion losses, in turn, reduce a range site's potential to produce vegetation cover; consequently, the original level of cover cannot be reestablished or maintained. Thus, as cover is reduced, soil loss increases; and as soil loss increases, cover is further reduced. Loss of vegetation cover by fire, drought, overgrazing, or other severe disturbance may be instrumental in initiating this degradation scenario. Also, gullies and channels are formed and cannot be reshaped and stabilized as readily as can be done on cultivated land (Wight and Siddoway, 1982). In these situations, the concept of thresholds may be useful when establishing soil T values. However, thresholds should be viewed not as sharp lines or specific values but, instead, as a range of conditions where the steady-state balance between erosion and soil formation have been irreversibly moved away from a desired balance. This results in a new balance that does not provide adequate plant cover to protect the soil resource.

T Values on National Forests

A concerted effort is currently being made by regional soil scientists within the United States Forest Service to develop soil quality standards and strategies for monitoring these standards. Most of these documents are now in draft form and will be finalized shortly. Development of soil quality standards are being coordinated among regions having similar soil impacts and problems.

Current erosion prediction of soil loss rates on National Forest Systems involves using the USLE. Soil losses are evaluated within the context of potential soil losses, natural soil losses, current soil losses, and tolerable soil losses. Potential soil losses are those that would occur upon complete removal of the vegetation and litter. Natural losses are those associated with climax vegetation. Current soil losses are those occurring under present management conditions. Tolerable soil loss is assumed to be the rate that can occur while sustaining inherent site productivity. These soil T values will also reflect the effect of shallower soil depths on productivity (i.e., shallower soils have lower soil T values).

STRATEGIES FOR ACHIEVING SOIL LOSS TOLERANCES

Most strategies for attaining acceptable soil T values are based on maintaining adequate levels of OM and/or reducing erosion losses. On some eroded rangelands, grazing management alone may be sufficient to improve plant vigor and restore OM. At the other extreme, intensive erosion rehabilitation programs may be necessary in order to restore badly deteriorated rangelands.

Residue Management

Improvement of site productivity on rangelands by residue management is limited to those areas where plant biomass can replace the erosional losses of soil OM. The magnitude of residue replacement rates necessary for replacing OM losses by erosion, however, may severely limit using this practice on rangelands. Calculations using a soil OM model based on ryegrass decomposition rates showed that long-term annual supplemental additions of about 1.8 Mg ha^{-1} of organic carbon (or 3.0 Mg ha^{-1} of OM, assuming OM is 60% OC) would be required to counterbalance soil losses of 11.2 Mg ha^{-1} (Alexander, 1988b; based on data of Jensinson and Raynor, 1977). Only the most productive grasslands could potentially produce the 3.0 Mg ha^{-1} of biomass required to replace erosion rates of 11.2 Mg ha^{-1} (5.0 t ac^{-1}.). This assumes that all the plant biomass is returned to the soil and is not harvested by grazing animals. Therefore, residue management of native plants simply could not restore erosion losses on severely deteriorated rangelands such as are found in the Southwest, which may produce only 300 kg ha^{-1} or less of herbage annually. Further, supplemental addition of OM is probably not a viable management alternative on most rangelands because, on a per unit basis, they are of relatively low economic value and cannot support the same level of investments afforded forest and cultivated lands (Wight and Siddoway, 1982). In summary, it appears that opportunities for ameliorating the effects of erosion on soil productivity by residue management are limited on rangelands.

Erosion Rehabilitation

Rehabilitation treatments to improve severely deteriorated rangelands may require complex and expensive mechanical treatments, such as contour furrows, pitting, and trenches. This is because improved grazing management alone cannot restore plant cover, and expanded channel networks may continue to erode and transmit unfavorable flows rapidly.

When plant cover cannot be improved by grazing management alone, grass seeding and mechanical treatments may be necessary to retain water and aid in vegetation establishment. These treatments may require several years of rest from grazing to allow plants to become well established before grazing is resumed. Mechanical treatments of various intensities, varying from contour trenches to ripping, discing, and pitting, have been used successfully for improving plant growth and vigor on rangelands. Contour trenching, although very expensive, has been used to improve high-elevation, deteriorated grass-covered watersheds throughout the West (Copeland, 1960; Bailey and Copeland, 1961). Although many erosion rehabilitation treatments are expensive, they may need to be applied only to select problems areas and not entire watersheds, thereby improving their practicality.

CONCLUDING REMARKS

The theoretical framework used for developing soil T values on croplands provides a useful conceptual framework for developing T values for rangeland soils. A basic assumption of this approach is that T values reflect a steady-state balance between soil formation and soil loss under climax vegetation where long-term soil productivity is not impaired. However, much of the information needed to develop acceptable soil T values for rangelands is not scientifically well supported (e.g., rate of soil formation, damage to deep fertile soils as the rooting depth is reduced, and effects of soil erosion on soil productivity).

The successful development of soil T values for rangelands requires better information on soil losses in response to a wide range of specific land management activities, ranging from grazing to mining disturbance. This information is needed to validate and refine current erosion prediction models (e.g., USLE, WEPP). It is difficult to establish T values for rangelands when the errors in soil-loss measurements may exceed the T values that should be established. The development of erosion prediction methodology on rangelands must be paralleled by basic research on the factors affecting soil formation and erosional processes in rangeland environments.

Recent data on soil formation rates in grasslands suggest that former soil T values developed from croplands are much too high. Maximum T values, based on plant responses from croplands after being reduced for shallower soils under grasslands, are currently proposed to be about 4.5 t ha^{-1} yr^{-1} or less depending on soil depth. The maximum annual rates of soil formation from lithic and paralithic bedrock on watershed supporting grass vegetation appear to be less than one-half metric ton/ha. This is much lower than current guidelines recognize.

Currently, we have a very superficial understanding of rangeland soils, and little is known about the effect of soil loss on the sustained productivity of different rangeland soils subjected to a wide range of uses. Until direct cause-and-effect relationships and the reversibility and irreversibility of impacts are better understood, T values for rangelands will probably remain subjective within the general conceptual framework of erosion losses and soil formation.

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SOIL ORGANIC MATTER AS A MEASURE OF FOREST SOIL PRODUCTIVITY: SOME CRITICAL QUESTIONS

John I. Blake and Gregory A. Ruark *

ABSTRACT

Economic and other social concerns make it desirable to regulate and monitor those forestry practices that have the potential to reduce soil productivity. If the intent is to collect soils data as part of a soil quality monitoring program, then it is imperative that a model or framework exists to process or interpret the data. Constraints on the interpretation of the soil organic matter (SOM) status preclude making accurate predictions of impacts on potential site productivity. This results from an array of confounding influences which limit generalization of existing databases and by a lack of understanding as to the actual proportion of the variation in soil productivity that is attributable to SOM components. It may be feasible, however, to predict the magnitude and direction of change in forest productivity by coupling disturbance processes affecting productivity with the changes in the levels of SOM components using Fuzzy Set procedures. The potential for future research to set SOM standards for monitoring would be considerably enhanced if further experiments tested models relating components of SOM to forest productivity rather than simply generate additional measures of treatment effects.

INTRODUCTION

Forest soil organic matter (SOM) is represented by a tremendous array of components including the surface litter, coarse woody debris, soil humic substances, various physio-chemical fractions, roots, fauna, and microorganisms. Their contribution to the total SOM status of the soil varies with climate, soil genesis, vegetation, and disturbance history (Schlesinger 1977, Spain et al. 1983). Relating SOM to soil productivity ideally involves establishing a direct quantitative relationship between a set of functionally defined SOM components and some measure of soil productivity, such as standing biomass, site index, net increment, or growth over a time interval (Powers et al. 1990). In practice, the relationship has been established indirectly by extrapolating the effect that changes in SOM components have on resource availability through model simulations (Harmon et al. 1986, Aber et al. 1982) and generalized productivity indices (Gale and Grigal 1990), by extrapolation of correlations between SOM components, soil properties and plant growth under different conditions by analogy (Brendemuehl 1967, Carmean 1975), and by inference procedures, whereby management practices, associated changes in SOM levels, and productivity are correlated (Woods 1980, Fox et al. 1989). Past research has relied heavily upon gauging the relationship from the effects of SOM on specific soil properties, rather than direct assessments of growth or yield (Chaney and Swift 1984).

Some general sampling procedures for monitoring forest soil quality were proposed by Hazard and Geist (1984). However, the specific biological, chemical, or physical components that must be sampled to obtain fractions of functional significance (i.e. water, nutrition, porosity, and amelioration of phytotoxic

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USDA Forest Service,
Savannah River Forest Station and
Southeastern Forest Experiment Station,
respectively

ions or organic chemicals) to forest soil productivity were not defined. Estimates of SOM levels will also be affected by the separation and extraction procedures used (e.g. Binkley and Hart 1989). For example, if identification and importance weighting of soil horizons is based on their taxonomic characteristics, then rankings may not accurately represent their nutritional contribution to the flora (Richards 1981). Regardless of the sampling and isolation method used, the current recommended analytical procedure is to report SOM values in units of total elemental carbon (C) (Nelson and Sommers 1986). This avoids confounding differences in oxidation state of C and elemental proportions in complex organic molecules (i.e. ratios of C:O:H:N).

If the goal is to monitor soil quality in order to more effectively regulate management activities (as contrasted with simple documentation), then the appropriate sampling will depend upon the precision and accuracy desired relative to the mathematical limits imposed by the model used to relate SOM to productivity. Therefore, a critical first step is to quantify the relationship between observed SOM and soil productivity (Blake et al. 1987). With simple relationships, techniques such as statistical differentials can be applied to determine how errors in several predictor variables will interact to reduce the precision of a derived estimate (Kempthorne and Allmaras 1986). These and other procedures can also be used to assign priorities to research efforts to improve predictability. The objective of this paper is to analyze several key questions to determine if reasonable inferences about soil productivity can be drawn from quantitative measurements of SOM status.

SOM AND PRODUCTIVITY: SOME IMPORTANT QUESTIONS

While "improvements" in soil properties from the retention or addition of organic matter have been repeatedly demonstrated (e.g. Khaleel et al. 1981), unequivocal evidence that critical levels of SOM exist in intensively managed agricultural systems is lacking. With prudent tillage and fertilization that are designed to minimize or mitigate soil displacement and compaction, while maintaining fertility levels, soil productivity can be sustained (Sanchez et al. 1983, Table 1). This is evident in the absence of external SOM inputs and even with declining SOM levels (Droeven et. al 1981, Fig. 1). However, regulation of SOM status is undoubtedly important in forest and agricultural systems in which opportunities to utilize technology to improve, sustain, or mitigate degradation of soil conditions are limited (Cole et al. 1987, Sanchez et al. 1989).

Table 1. Trends in surface SOM content and crop yields (in rotation) in the Peruvian Amazon following slash and burn conversion of native forest to cultivated farmland. Yields are for complete nutrition plots. Check plots averaged less than 0.5 kg grain ha^{-1} x 10^3 per harvest (from Sanchez et al., 1983).

Time after Conversion	SOM	Corn	Soybean	Rice
months	% C	Grain (kg ha^{-1} x 10^3 per harvest)		
0	1.21	---	---	---
1	1.38	---	---	3.3
6	1.40	1.5	---	3.0
12	1.12	---	1.8	3.2
20	----	2.8	2.3	1.9
36	1.05	2.3	1.8	2.3
42	1.32	4.0	2.9	2.6
60	1.36	3.3	2.3	2.4
66	1.00	3.6	---	3.6
72	1.15	3.6	2.8	2.5
84	0.95	3.0	1.9	2.1
96	1.05	2.9	2.6	---

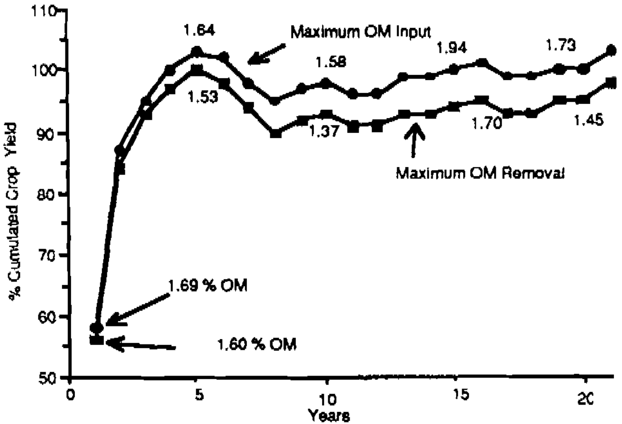

Fig. 1. Effect of organic matter removal and inputs on cumulative crop yield (adapted from Droeven et al. 1981).

The data in Figure 2 demonstrate the range in productivity associated with SOM levels where attempts were made to maintain adequate nutrition and minimize erosion losses (Lucas et al. 1977). The relationships may reflect the effect of SOM on water holding capacity and porosity.

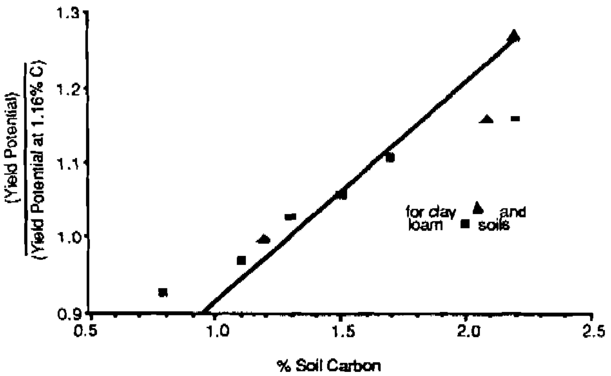

Fig. 2. Crop yield in North Central United States (after Lucas et. al. 1977)

Measures of Soil Productivity

What is a suitable measure of soil productivity- gross primary productivity, site index, growth rate or increment, standing biomass, total biomass, or simply an index of specific soil properties? The quantitative relationship between soil productivity and SOM will change as a result of differences in the definition of productivity. While site index is a common measure of productivity, native species can show varying sensitivity in growth to varying soil conditions (Olson and Della-Bianca 1959). Also, it is difficult to accurately interpret site index in terms of biomass without defining stocking levels, or to extrapolate initial difference in height growth following treatment to index values at subsequent ages. Similarly, there are substantial data indicating that above-ground biomass is not a constant proportion of total ecosystem biomass (Harris 1981, Cannell 1985), or an accurate indicator of gross primary productivity (Sauerbeck and Johnen 1977).

Data from a study by Ojeniyi and Agbede (1980) illustrate another problem with quantitative development of a SOM-productivity function (Figure 3).

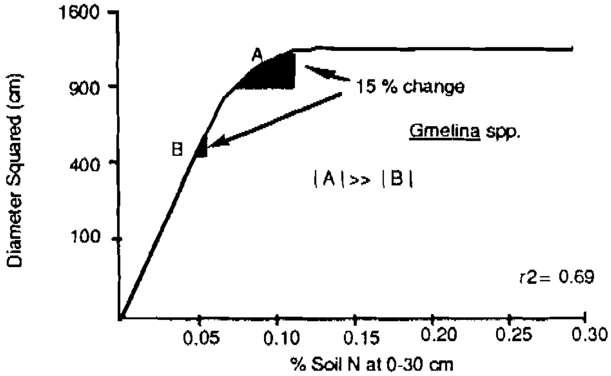

Fig. 3. Effect of 15 percent change in productivity at two different levels (adapted from Ojeniyi and Agbede 1980)

A direct relationship between basal area growth of Gmelina and levels of SOM (% C, 0-30 cm) occurred. If a 15% productivity decline is used as a threshold to indicate unacceptable impairment, this value will not represent equivalent amounts of absolute growth lost across a range of sites. Consequently, in economic terms a 5% decline in growth on highly productive sites may be equivalent to a 30% decline on low productivity sites. From a practical viewpoint, the definition of soil productivity will be determined by the databases available, but the consequence of having an array of arbitrary measures of productivity will be a reduction in the utility of specific quantitative assessments.

Relating Levels of SOM to Productivity

What evidence exists to quantitatively relate SOM to soil productivity, and can these observations be generalized to create a reasonably precise framework for assessing impacts to soil productivity? In establishing an interpretative framework for monitoring SOM, some reliance must be placed on empirical relationships between the status of SOM and measures of soil productivity and heuristic observations relating management activities to alterations of SOM and forest growth. These databases include soil-site correlation studies, silvicultural treatment impacts, retrospective studies, and controlled experiments in which SOM related properties have been manipulated. Not only does this information provide direct evidence for the sensitivity of soil productivity to changes in SOM components, it also serves as a basis for evaluating our understanding of the processes that regulate forest soil productivity. However, assessing impacts to soil productivity using only the relation between SOM and specific soil properties remains speculative (Sands 1983). Operational estimates based largely on simulations of the dynamics of SOM components, functional soil properties, and plant growth (Kimmins 1977) are not appropriate at this time. Although excellent research tools, these models often represent generalized plant-soil productivity relationships as fairly complex hypotheses that have not yet been tested.

The largest databases for potentially relating SOM components to productivity are soil-site correlation studies. Although the depth of the "A" horizon is often positively related to site index (Carmean 1975), these studies suggests that the importance of measured SOM to soil productivity varies. Early work by Wilde et al. (1965) showed a strong positive correlation (r = 0.58 to 0.69) between jack (P. banksiana) and red pine (P. resinosa) productivity and percent SOM in the surface soil on coarse glacial deposits in Wisconsin. These studies were conducted using plantations established on abandoned agricultural lands. In studies with natural stands of western hemlock (Tsuga heterophylla Sarg.) in Oregon, a strong positive correlation between total SOM and site index was also found (Meurisse 1978).

However, weak positive, or at times negative, correlations between site index and surface soil SOM have been reported for other species (Broadfoot 1969, Peterson et al. 1984, Heilman 1978). To reduce variability, McKee (1977) examined the relation between site index of loblolly pine (Pinus taeda L.) and percent total SOM in the surface soil, separately for three soil series. He found no significant correlations with site index and in addition, two of the three coefficients were negative. These results likely reflect strong co-variance between SOM and pedogenic processes, or between SOM and stage of stand development. Nevertheless, they indicate that quantitative measures of total SOM status are not likely to consistently account for a large fraction of the variance in soil productivity across the landscape.

It would be easier to make inferences if we could demonstrate that levels of SOM are almost always below a threshold that limits soil productivity, whereby any reduction in SOM resulted in a proportional productivity loss. Brendemuehl (1967) demonstrated this type of relation with slash pine by removal of organic layers from a coarse textured soil in Florida (Fig. 4).

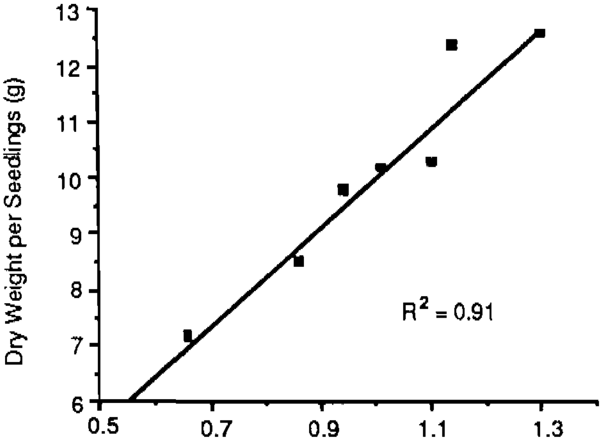

Fig. 4. Effect of topsoil loss on growth of slash pine seedlings (after Brendemuehl 1967)

Lutrick et al. (1986) observed the same response by increasing SOM through sludge additions (Fig. 5).

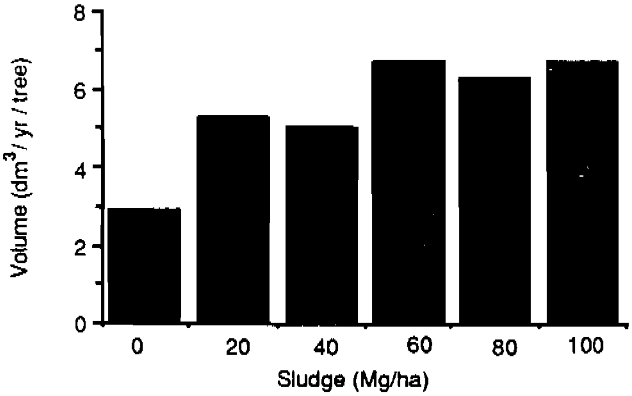

Fig. 5. Effect of sludge applications on volume growth of slash pine seedlings nine years after treatment (adapted from Lutrick et al. 1986)

In southern Australia on deep infertile sands SOM conservation has enhanced radiata pine (*Pinus radiata* D. Don) productivity (Squires et al. 1985). However, since mechanisms contributing to improved productivity are complex, involving both mulch and nutrition effects, similar behavior may not be observed where one or more of the contributing factors is eliminated (Turvey and Cameron 1986). Table 2 shows that raking of slash debris reduced early growth only if competing vegetation was not controlled.

Table 2. Effects of windrowing logging slash and weed control on radiata pine growth at 8.5 years following treatment. Adapted from Turvey and Cameron's (1986) study in eastern Victoria, Australia. Numbers followed by the same letter are not significantly different at p= 0.05.

Weed Control	Slash Windrowed	Height	DBH	Stocking	Basal Area
		m	cm	stems ha-1	m2 ha-1
No	No	9.8b	11 1b	1441a	14.9bc
No	Yes	9.1c	10 0c	1585a	13.7c
Yes	No	10.5a	11.6a	507a	17.2b
Yes	Yes	11.1a	12.1a	1659a	20.3a

It may not be appropriate to generalize about management impacts unless the soil-plant mechanisms are established and they can be related to the intensity of activity (Ballard 1978, Waldrop et al. 1987).

With the exception of highly disturbed, very coarse textured soils, or those subject to extremely rapid decomposition, it seems likely that thresholds exist beyond which further addition of specific SOM components contribute little to productivity. This is illustrated in Fig. 3 and by Laatsch (1962) and Powers (1980) where mean annual increment and potential N-mineralization are compared. Similarly, the first rotation burning study of Morris (Kraemer and Hermann 1978) in Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) indicated that soil productivity in this region may be sufficiently buffered by soil and plant successional mechanisms so that significant losses of the forest floor can occur with little change in observed productivity (Miller and Bigley 1989). While SOM levels can affect soil productivity, relating standing crop estimates to productivity is difficult due to non-linear responses. Comparison of productivity with SOM between locations is often confounded with other growth factors and among sites by the many functional mechanisms which link SOM to productivity.

Disturbance and Dynamics of SOM

Does the process by which SOM levels are altered (combustion, decomposition, erosion, and harvesting) affect the relationship between SOM and soil productivity? Each one of these processes can create similar levels of SOM, but it seems unlikely that the consequences for soil productivity would be equivalent. Observations that some treatments can reduce SOM substantially while actually increasing apparent productivity further complicates interpretation of SOM measurements (McKee and Shoulders 1974, Weetman et al. 1990). For example, thinning stands has been demonstrated to decrease surface soil SOM through accelerated decomposition (Piene 1978), but with a subsequent increase in growth attributed to higher N-availability. Similarly, residual stocking has been shown to be related directly to SOM accumulation (Wollum and Schubert 1975, Carey et al. 1982), as a result of changes in litter inputs, as well as decomposition. Comparisons among tree species also indicates that substantial differences can exists in SOM accumulation and nutrient turnover (Alban 1979). Is it acceptable to regard these disturbances as having the same impact as a similar effects resulting from litter raking or burning (McLeod et al. 1979, Waldrop et al. 1987)?

Perhaps the greatest impediment to the use of standing crop measures of SOM to monitor soil productivity is the intrinsic dynamics of SOM in forest ecosystems (Covington 1981, Fig. 6).

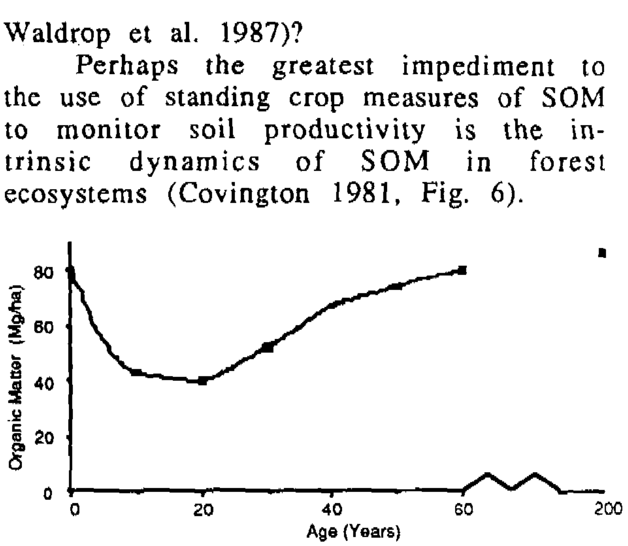

Fig. 6 Forest floor organic matter content in northern hardwood stand (adapted from Covington 1981)

Without significant SOM turnover productivity would eventually be reduced by nutrient immobilization. Figure 7 illustrates the importance of SOM turnover using the data from Miller (1987) and Carlyle and Malcolm (1986)

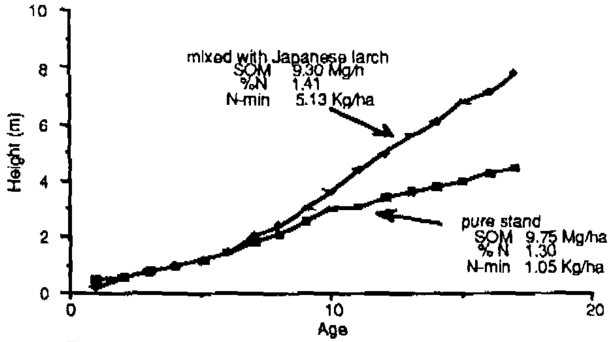

Fig. 7 Effect of soil organic matter and nitrogen mineralization on height growth of Sitka spruce (adapted from Miller 1989 and Carlyle and Malcolm 1986)

Growth of sitka spruce (Picea sitckensis (Bong.) Carr.) is more closely associated with the mineralization rate potential of the SOM than to the absolute quantity of SOM. Basic research also provides evidence that nutrient turnover rates are more closely related to productivity than the amount of SOM per se (Cole and Rapp 1981). Similarly, equations for predicting N-fertilization responses and N-uptake show that variation in the factors regulating decomposition (C/N ratio, moisture, temperature) are often of greater importance than the amount of SOM (Laatsch 1962, Edmonds and Hsiang 1987, Binkley and Hart 1987, Richards 1981).

Another consequence of intrinsic dynamics is that soil productivity should be sensitive to variations in the levels of the most labile components of SOM, as they control nutrient cycling. For components that are relatively non-labile, it can be difficult to establish their importance. This may arise because quantities are almost always above levels which cause detectable changes in productivity or because their functional value to soil productivity is relatively minor. In particular, the role of large organic debris and bole wood in cool temperate forests (Harmon et al. 1986, Jurgensen et al. 1987) and non-labile soil organic fractions in the mineral soil are subjects of debate.

For large woody material, part of the problem results from their slow decomposition-incorporation rate in temperate forests (Edmonds 1979, Sollins 1984) and their horizontal and vertical dispersion in the soil. For the non-labile SOM fraction in the mineral soil, the functional value is largely equated with nutrient retention or water availability in the surface layer. However, both variables are difficult to quantitatively relate to forest productivity.

Sample Estimates

What variables might affect the sampling protocol? Traditional sample designs, spatial statistics, and analytical techniques can be used to deal with precision and interpolation for individual components as they relate to the sample population. However, these procedures may not effectively deal with the spatial and temporal characteristics of SOM that can reduce the accuracy of estimates. High variability among locations make absolute measurements of total SOM of limited value, unless losses of SOM are severe. Total SOM measures need to be related to similar areas in order to provide a baseline for comparison. Since operational units are rarely designed with the same interest in replication and uniformity as research plots, the default baseline reference for comparison will be the SOM level on the site prior to treatment.

Data reported by Haines and Cleveland (1981) (Fig. 8) demonstrate that temporal sampling variation in surface SOM can be large.

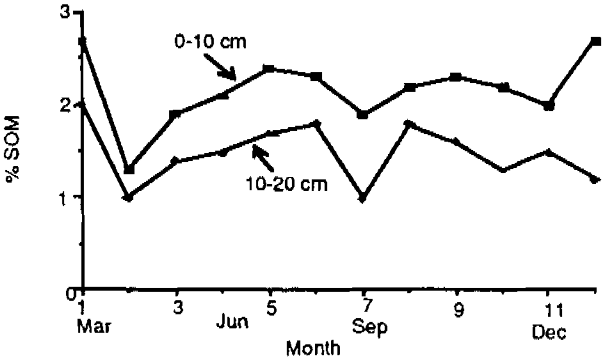

Fig. 8 Monthly variation in percent total soil organic matter in a 6 year-old slash pine plantation on a Typic Paleudult (adapted from Haines and Cleveland 1981)

This makes accurate baseline determinations of SOM levels difficult, especially if estimates of the highly labile fine root fraction are important. Presumably, components with slower turnover rates, e.g. large woody debris, or more recalcitrant fractions in the soil profile would not have the same degree of variability.

Figure 9 shows a conceptual view of SOM. Currently we measure total SOM, but the value observed can vary greatly by season. This poses a problem in deciding which value to relate to soil productivity potential. The large short-term variation in total SOM is likely due to highly dynamic fine root turnover. As such, we need to identify a stable baseline measure which represents the separation between the extremely labile SOM pool and relatively recalcitrant SOM. This new baseline measure would be independent of season of sampling and would better reflect the long-term status of SOM. A shift in this baseline as a result of disturbances, such as burning or erosion, would constitute a long-term alteration in soil productivity potential. A significant decrease in the labile pool level would reflect short-term impacts on productivity, but this pool might be expected to recover from disturbances over a relatively short time frame through inputs of fine root and litterfall debris.

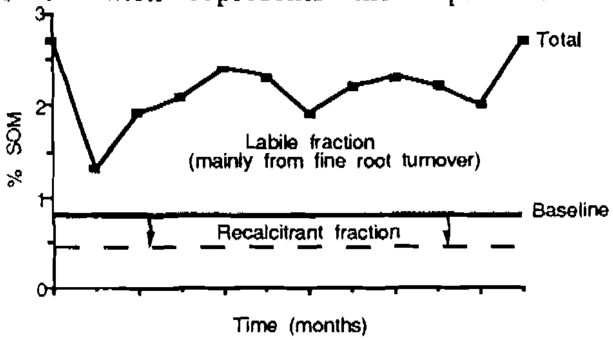

Fig. 9 Baseline shifts in the short-term occur mainly through soil displacement or burning. It is when the baseline shifts that long-term soil productivity is lowered. Increases or decreases in the size of the labile fraction occur over the short-term.

Spatial problems resulting from redistribution of foliar litter are demonstrated by the data of Shure and Phillips (1987) (Fig. 10). Considering the movement away from large clearcuts on National Forests, the larger ratio of unit boundary to unit area will affect measurements of forest floor SOM and ultimately SOM levels for many years following disturbance.

BOOTSTRAPPING

The direct response information base that we possess is more like a collage rather than a functional data set. This leads to pattern matching of management practices with disturbances that we construe to represent the effects of SOM on soil productivity. This mental association guides expectations about productivity to a far greater extent than is supported by existing information. This is not meant to imply that existing observations are useless in establishing a relationship. However, the ability to make strong inferences about threshold values and sensitivity to management activities among locations is limited. It is difficult to justify measuring only a single SOM component at this time since SOM can influence productivity via a number of processes, and the functional roles of many components are still uncertain. The dynamic temporal and spatial behavior of SOM also complicates assessment.

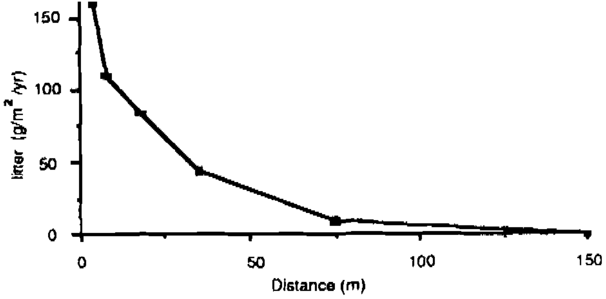

Fig. 10 Distribution of leaf litter from edge to center of forest opening in a southern Appalacian forest (adapted from Shure and Phillips 1987)

Flexible methods exists for utilizing data for which the relationships are vague, general, and highly variable. Specifically, "Fuzzy Sets" theory

(Burrough 1990) offer an opportunity to extract information about overall soil degradation and integrate effects on SOM, porosity, and erosion (Gale and Grigal 1990). In addition, fuzzy sets interface well with spatial analysis programs and local expertise. This technique does not overcome problems with sampling a dynamic SOM component, setting objective threshold limits, or interpretation of SOM interactions with other soil properties. However, it does permit greater flexibility in utilizing a wide range of information sources, to set threshold standards.

Improving the Information Base

While recent studies in agriculture support the results of mechanistic based model simulations of SOM management on crop productivity (Jenkinson and Rayner 1977, Parton et al. 1983), similar approaches have not been adequately tested in forest systems. However, a great deal is known about how SOM influences plant-soil relationships, such as soil porosity, water availability (Sands 1983), nutrient availability, metal complexes, soil thermal regimes, micro-organism habitat etc.. For forest systems, removing some of the fuzziness and bias associated with impact prediction will require coupling long-term experimental or operational studies of treatment impacts to functional models of soil productivity. This means using these studies to test predictions and hypotheses about the processes which link SOM to productivity, rather than just expanding the database on treatment response. From the practical standpoint of improving SOM monitoring for quality control purposes, in contrast to simple documentation, the approach outlined by Sollins et al. (1983) for linking basic studies of SOM to operational practices is desirable.

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SOIL PHYSICAL PROPERTIES AS A MEASURE OF CROPLAND PRODUCTIVITY

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ABSTRACT

The major objective of this paper is to identify physical parameters as well as threshold values to serve as an early warning signal of reduced productive capacity of soils common to the U.S. Corn Belt. Specific physical parameter and threshold values are suggested for both surface layer and subsoil. Changes in the surface layer properties that effect productivity include: erosion phase, aggregation, organic C, infiltration, texture, and coarse fragments. Changes in the subsoil properties that affect soil productivity include: mechanical strength, aeration porosity, water storage porosity, residual porosity, bulk density, permeability, and rooting depth. Two processes which have a major impact on soil physical conditions and productivity are erosion and soil compaction. Minor (15%) and major (25%) reductions in inherent productivity are suggested as a basis for setting threshold values for measurable and observable soil physical properties or conditions based on current methods, technology, and reasearch. The threshold values are suggested to serve as indicators of reduced productive capacity. These physical parameters and specific threshold values are based on erosion-productivity relationships shown to affect soil conditions in the U.S. Corn Belt and could vary with location, crop, soils, management, and climate.

INTRODUCTION

Soil Quality Standards

The major purpose of soil quality or condition standards is to identify threshold physical values to serve as an early warning signal of reduced productivity capacity of soils common to the U.S. Corn Belt. The goal of soil quality standards would be to maintain, restore or enhance the inherent long term soil productivity. The physical quality or condition of a soil is a consequence of the effects of land use and management on the physical, chemical, and biological processes occurring within the soil. Any attempt to monitor soil quality or condition requires the development of arbitrary standards for soil disturbance or modification. Soil management changes may improve or damage the soil to support specific agricultural crops. Management changes may be long or short term, significant or insignificant, and may improve or damage the natural soil productivity. Changes may be hydrologic, mineralogic, biological, chemical, or physical. Emphasis in this presentation will be given to physical standards and conditions, but soil quality or condition standards must include the other soil properties that affect soil productivity. Changes in bulk density, pore size distribution, aggregation, texture, organic carbon, thickness of topsoil and rooting depth can be used to define significant changes in soil productivity over the short or long term. Monitoring of specific soil physical properties could be done to determine if soil productivity objectives are being achieved. Minor (15%) and major (25%) reductions in inherent soil productivity could be arbitrarily selected as a basis for setting threshold values for measurable and observable soil properties or conditions based on current technology and research. The threshold value for each physical parameter is to serve as an indicator of reduced productivity capacity of a soil. The concepts of soil productivity, organic carbon, aggregation, pore size distribution, and water releases, as well as the purpose of this paper, are discussed below.

Soil Productivity

Soil productivity is often defined as the capability of soil to produce a specified plant or sequence of plants under specific management. Olson and Olson (1986) generalized the relationship between crop yield and production factors in the following equation:

Yield = f [climate, management, site, topography, soil characteristics (chemical, physical, mineralogic and biological), and time]

Organic Carbon

Organic matter is an important constituent of soils and can affect productivity. The amounts range widely in various soils under different environmental conditions and systems of management. In soils that contain little organic matter, the amount can be increased by suitable cropping and management practices. In soils that are naturally high in organic matter (above 3%), tillage and cropping tend to accelerate decomposition of organic matter. Whiteside and Smith (1941) found a 23% decline in organic C when comparing an intermittently cultivated from 1850s to 1935 with adjacent virgin soils (from 3.17% to 2.44% organic C). The goal of sound management is to maintain organic matter at desirable levels in various soils. The organic matter content of soils which are naturally low (below 1%) can be increased by using crop rotations which include a forage crop. When soils are intensively row cropped, problems with weak aggregation and crusting are greater particularly when the organic carbon content drops below 1.5%, especially in silty or loamy soils.

Aggregation

A soil aggregate is a naturally occurring cluster of inorganic and organic particles combined such that the strength of forces holding the particles within the aggregate exceeds the strength of the external forces applied from the environment in which the aggregate exists (Farres 1980). Soil structure is customarily defined as the arrangement of the soil particles and refers to either a primary (sand) or a secondary (aggregate) particle. Specifically, Brewer and Sleeman (1960) defined soil structure as "the size, shape, and arrangement of primary particles to form compound particles and the size, shape, and arrangement of compound particles."

It has been recognized for a long time that organic matter serves as a cementing agent in soils (Baver 1935). Sideri (1936) suggested that humus is adsorbed by clay through the process of the orientation of organic molecules on the surface of clay particles. Kubiena (1938) suggested that the genesis of the films or binding materials depended upon the dehydration process and associated precipitation of dissolved constituents. Martin (1946) and Peerlkamp (1950) attributed the cementation of soil particles to certain polysaccharides formed during decomposition of organic residues by microbiological activity, as well as cementation by bacteria and fungi. Martin (1971) suggested that polysaccharides bind to soil particles as a consequence of the physical characteristics of these molecules and their functional groups.

Edwards and Bremner (1967) proposed a mechanism that describes the effect of cations on polysaccharide bonding to and linking clay particles. Their analysis indicates that divalent cations share some of their valence with the clay-cation-exchange complex. The cation thus acts as a "bridge" or connecting mechanism between the clay surface and the polysaccharide. The cation serving as the "bridge" apparently influences the strength with which the polysaccharide is adsorbed and, therefore, aggregate stability. A variety of studies have shown that monovalent cations, such as Na^+ and K^+, having large ionic radii, result in more weakly developed soil structure conditions than do exchangeable divalent or trivalent cations, such as Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+} (Guckert et al. 1975; Edwards and Bremner 1967; Saini and MacLean 1966).

In addition to important organic and inorganic constituents, cycles of wetting and drying have been related to the increased formation of aggregates in nonaggregated soil (Utomo and Dexter 1982; Telfaire et al. 1957). Richardson (1976) suggested that cycles of wetting and drying can restore some structurally damaged soils.

Pore Size Distribution and Water Release

The relationship between pore size and water potential has been established. Russell (1973) found that soils drain freely under gravity to a water potential that is unlikely to be lower than -0.05 to -0.10 bars and that the pores smaller than 30 to 60 µm will be water-filled. The larger pores will be air-filled. Water in pores of diameters less than 0.5 µm and a potential below -15 bars (Arkin and Taylor 1981) is unavailable to the roots. Plants could not remove water from these small pores due to high adhesion. Greenland (1977) proposed the terms transmission, storage, and residual for three respective class sizes of soil pores with equivalent pore diameters of 50 and 0.5 µm separating the respective classes.

Purpose

The objectives of this paper are to (1) identify physical parameters and measurement methods for both the soil surface layer and subsoil which relate to the productive capacity of soils, and (2) establish threshold values for physical properties to serve as an early warning signal of reduced productive capacity of soils.

METHODS

Bulk density (33 kPa), water-retention difference (WRD), and porosity can be measured using saran-coated clods and sieved samples, using the procedures outlined by Soil Survey Staff (1984). Aggregate stability can be measured by a wet-sieving technique (Kemper and Rosenau, 1986). Pore distribution can be measured within freeze-dried soil samples using a Hg-intrusion porosimeter (Olson, 1985; 1987; 1988). Alternatively, pore size class and corresponding volumes can be calculated using water release (Olson and Jones, 1988). Residual pores can be calculated from 1500 kPa moisture (% by weight) times bulk density at 33 kPa and divided by the density of water. The water storage pores are equal to WRD, and the transmission pores equal the [total porosity (%) minus (the sum of water storage (%) and residual pores (%))]. Total porosity is equal to [100% - (100% x bulk density at 33 kPa divided by the measured particle density using a He pycnometer)] (Olson and Zobeck, 1989). These moisture release values have been shown by Olson (1985) to correlate well with those measured directly by Hg intrusion. The infiltration rate can be determined using the method by Bouwer (1986) and the percolation rates using the Klute and Dirksen (1986) method. The particle-size distribution of the < 2-mm fraction can be measured using the pipette method and sand sieving (Soil Survey Staff, 1984) and the organic carbon using a modification of the Walkley-Black wet oxidation procedure (Nelson and Sommers, 1982). Erosion classes and phases can be identified in the field using the USDA method (Soil Survey Staff, 1984) which relates to percentage loss of original A horizon of a pedon.

EFFECTS OF COMPACTION ON SOIL PROPERTIES AND PRODUCTIVITY

The effect of compaction on plant growth, root growth and yield depends on the crop grown and the environmental conditions that the plant encounters, which are determined by the soil and the weather. The compaction variables are, in turn, affected by management factors such as nutrient status. Soil compaction occurs when a load (stress) is applied to the soil and a volume change (strain) results as a consequence of the rearrangement of particles (Arkin and Taylor, 1981). This change can usually be quantified by changes in bulk density, porosity, or void ratio. Swan et al. (1987) indicated that soil compaction refers to the packing effect of a mechanical force on the soil. As a consequence, the volume occupied by pores decreases, the density and strength of the soil mass increases, and the number of large pores decrease (Swan et al., 1987).

Larger sizes and greater weights of farm tractors are causing increased concern about soil compaction (Voorhees et al., 1978). Results from earlier studies on longevity of wheel induced compaction in the Corn Belt (Gill, 1971) have suggested that compaction was not a problem north of the "hard-freeze line". Other researchers (Bauder et al., 1981) have found that years of cropping and cycles of freezing and thawing did not alleviate a compacted soil layer at the bottom (15 to 25 cm depth) of the plow furrow. Controlled wheel traffic studies in Minnesota (Voorhees et al., 1978) have shown that wheel traffic of normal farming operations could compact the soil to a 45-cm depth and penetrometer resistance was found to be a more sensitive indicator of soil compaction than was bulk density. Soil properties, including bulk density and penetrometer resistance were shown by Cassel (1983) to vary temporally and spatially with tillage, depth, and by position (i.e. nontrafficked interrow, row, and trafficked interrow). Care must be taken to identify the time, depth and position at which the measurements were made.

The compaction effects of wheel traffic on soil can be quantified in terms of changes in pore size distribution. The soil pore size classes and volumes can be measured using Hg intrusion. By directly comparing the soil pore size distributions between the nontrafficked and trafficked interrows of a tillage system it was possible to determine the extent and depth of compaction caused by wheel traffic. Compaction caused by wheel traffic tended to increase water storage (50 - 0.5 um) pore volumes and decrease aeration (> 200 um) pore volume (Gill, 1971, Voorhees et al., 1978; Cassel, 1983).

EFFECTS OF SOIL EROSION ON SOIL, CHEMICAL, PHYSICAL, AND MINERALOGICAL PROPERTIES AND PRODUCTIVITY

Soil erosion affects the chemical properties of soils by: (1) loss of organic matter, (2) loss of soil minerals containing plant nutrients, and (3) exposure of subsoil materials with low fertility or high acidity. Soil erosion causes changes in physical properties of soils, such as structure, texture, bulk density, infiltration rate, depth for favorable root development, and available water-holding capacity (Batchelder and Jones, 1972; Frye et al. 1982). Soil erosion causes changes in mineralogical properties of soils by thinning the topsoil with tillage equipment mixing parts of the subsoil (B horizon) into the plow layer (Ap horizon). The clay mineralogy of a soil depends on the parent materials present, weathering, and clay redistribution (Nizeyimana and Olson, 1988).

Numerous factors such as weather and plant genetic potential control the overall production of crops in a given geographic area; however, the soil system remains a major determinant of yields because of the environment it provides for root growth. Early studies, such as Fehrenbacher and Rust (1956) found that root development and crop yields were positively correlated. Shallow rooting depths in some of the soils studied were caused by high clay content, acidity, or very dense materials.

Researchers (Olson and Nizeyimana, 1988) have evaluated the effects of degree of erosion on the chemical, mineralogical, and physical properties of seven Illinois soils. For most soils studied, degree of erosion significantly reduced the organic carbon, and water storage porosity values of the Ap horizons. Clay mineral type estimates of the Ap horizons of severely eroded soils change measurably as a result of thinner topsoils permitting the tillage equipment to mix underlying Bt horizon materials that are higher in hydrous mica or smectite into the topsoil. With increased degree of erosion, pH, cation exchange capacity, K and base saturation value trends varied with soil series. Erosion of soils with root restricting layers, such as dense subsoils, resulting in these layers occurring closer to the surface and in lower water storage capacities.

In the Midwest and Western U.S. precipitation and available soil water limit crop production when nutrients are in adequate supply. The extent of production loss on eroded soils depends largely on landscape position, runoff and internal drainage. Observations such as these are frequently independent of erosion intensity. For droughty areas which are highly eroded, residue maintenance on the soil surface can reduce runoff and increase infiltration and hydraulic conductivity in the top 20 cm.

Organic matter is important in both the development of structural aggregates and their stability (Baver et al. 1972). In the Corn Belt, aggregates stabilized by humus are more stable than those bound by clay. Subsurface aggregates low in humus are more easily broken down by the impact of raindrops and increase the rate of runoff. Reduced soil-water recharge potential can result in reduced productivity.

When clayey subsoil materials of an eroded soil are incorporated into the plow layer by tillage, the moisture range at which the soil can be easily and safely tilled become narrower (Frye et al., 1985). If the soil is tilled wet, soil structure tends to break down resulting in decreased pore space, aeration, infiltration and percolation, and increased bulk density. Soil compaction often becomes a problem. If tilled dry, the clayey subsoil becomes cloddy and difficult to work, thus, raising energy costs.

Erosion usually reduces the immediate and long-term crop production potential (Pierce et al., 1983). Attempts to collect data and provide current information on the effect of erosion on soil productivity have been made (American Society of Agricultural Engineers, 1985; Follett and Stewart, 1985). Priority needs to be given for research to determine the effect of soil erosion on crop production potential as related to soil properties (Larson et al. 1981; USDA Staff, 1984).

Erosion-related yield reductions have been attributed to loss of fertility (Bennett and Lowdermilk, 1983). However, fertilizer can extend or maintain the productive potential of some eroded soils. A study in Ohio (Uhland, 1949) showed reduced topsoil thickness resulted in reduced corn grain yields. Researchers in Illinois (Odell, 1956) found positive correlation of grain yields to surface soil thickness; and that surface soil thickness over favorable subsoil had little effect on yield, whereas reduced surface soil thickness over unfavorable subsoil decreased yields. Yield differences were thought to be due to differences in clay content and lower water-holding capacity. In Illinois, corn yields were related to depth of rooting and available soil water (Fehrenbacher and Rust, 1956). Root penetration was restricted by high bulk density, low aeration, and lack of structural development. Hairston et. al., (1988) found soil depth to be a much better predictor of yield at sites with low organic matter, especially when rainfall was also low.

In Kentucky, corn-grain yields were decreased 12 to 21% on eroded soils when compared with uneroded soils (Frye et al., 1982). In Illinois (Olson and Nizeyimana, 1988) soils formed in loess without root restricting subsoils showed only slight yield reductions (5%) with increasing degree of erosion and loss of topsoil (organic carbon). Greater corn (Zea mays L.) yield reductions (24%) did occur for soils with root restricting subsoils primarily as a consequence of reduced plant available water storage.

Organic matter content can be increased by mulch tillage (Beale et al., 1955). Over a 10-year period in South Carolina, corn grown by no-tillage in a vetch and rye mulch increased the soil organic matter, by degree of soil aggregation, and stability of the soil structure in the Ap horizon. Researchers (Salter et al., 1941) have shown a strong relationship between cropping system and soil organic matter content. Continuous corn had the greatest decrease in organic matter. Researchers (Frye et al., 1982) have found that restoring the organic matter of an eroded soil did less to restore the productivity of the soil than increasing the available water-holding capacity.

THRESHOLD VALUES FOR PHYSICAL PROPERTIES

Threshold values for physical properties that affect soil productivity need to be established for both the surface layer and the subsoil. As described above, the primary physical properties which affect productivity (Table 1) include: erosion phase, aggregation, organic carbon, infiltration, texture, and presence of coarse fragments. Minor (15%) and major (25%) reductions in inherent soil productivity are suggested as a basis for setting threshold values for measurable and observable soil properties or conditions based on current methods, technology and research.

Severely eroded soils have been shown by many researchers to lower crop yields. The magnitude of the yield decline (from 0 to 35%) is also related to root restricting nature of the subsoil. Aggregation has been shown to reduce soil loss, improve aeration, reduce crusting, and increase plant emergence. The presence of more than 1.5% organic carbon with significant amounts of polysaccharides in loamy and silty soils have been shown to enhance aggregation. Texture of the surface layer can also affect soil aggregates. Erosion and subsequent mixing by tillage can alter the surface texture which in some instances reduces productivity (Table 1). Coarse fragments also reduces rooting volume and available water.

Table 1. Threshold values for physical properties[a] of the surface layer which affect soil productivity.

Surface Layer Property	**No Reduction in Productivity**	**Minor Reduction in Productivity**	**Major Reduction in Productivity**
Erosion Phase	Slight	Moderate	Severe
Aggregation	>30%	20-30%	<20%
Organic Carbon	>1.5%	1.0-1.5%	<1.0%
Infiltration	>3 cm hr^{-1}	1-3 cm hr^{-1}	< 1 cm hr^{-1}
Texture of Ap Changed to:	Silt Loam, Silt, Loam	Clay Loam, Silty Clay Loam, Sandy Loam	Silty Clay, Clay, Sand, Loamy Sand
Coarse Fragments	<15%	15-35%	>35%

[a] Only physical properties have been included.

Physical properties which affect soil productivity of the subsoil (Table 2) included: mechanical strength (penetration), aeration porosity, water storage porosity, residual porosity, bulk density (33 kPa moist), permeability, and rooting depth (solum thickness). As the penetration resistance increases root ramification is restricted. Any reduction in root mass and elongation would adversely effect the ability of the roots to supply nutrients and water. Aeration porosity is important since roots grow in this size class of voids, water moves through under saturated conditions, and gas is exchanged. The water storage porosity provides water to the plant during dry periods. High bulk density, which is the inverse of low total porosity, correlates well with high mechanical strength. The 33 kPa bulk density values shown in Table 2 are for loamy and silty soils. The limits would be 0.10 to 0.20 Mg m^{-3} higher for sandy soils and 0.10 to 0.20 Mg m^{-3} lower for clayey soils. Residual porosity is only significant when the value becomes too high, such as for some fine and very fine textured soils. Permeability rates which are slow often cause perched water tables and waterlogged conditions which are adverse to the growth of many crops.

Table 2. Threshold values for physical properties[a] of the subsoil layer which affect soil productivity.

Subsoil Property	Reduction in Productivity None	Minor	Major
Mechanical Strength	<1500 kPa	1500-2500 kPa	>2500 kPa
Aeration Porosity	>20%	20-15%	<15%
Water Storage Porosity	>20%	20-15%	<15%
Residual Porosity	<15%	20-15%	>20%
Bulk Density[b]	<1.30 Mg m^{-3}	$1.30-1.65$ Mg m^{-3}	>1.65 Mg m^{-3}
Permeability	>1.5 cm hr^{-1}	$0.25-1.5$ cm hr^{-1}	<0.15 cm hr^{-1}
Rooting Depth	>1.5 m	1-1.5 m	<1 m

[a] Only physical properties have been included.

[b] At 33 kPa moisture content.

The suggested physical parameters and threshold values are based on previously cited research on erosion-productivity and compaction-productivity relationships in the U.S. Corn Belt and would need to be modified to fit other crop growing areas in the U.S. Differences in crops, soils, and climate require changes in the threshold values for a specific physical parameter or require the measurement of different physical parameters. Important chemical parameters were not the focus of this paper.

SUMMARY

Surface layer and subsoil physical parameters were identified along with threshold values to serve as an early warning signal of reduced productive capacity of soils. These physical parameters and specific threshold values are based on erosion-productivity relationships which have been established primarily in the U.S. Corn Belt and would vary with location, crop, soils, management, and climate. Changes in the surface layer properties which affect productivity include: erosion phase, aggregation, organic C, infiltration, texture and coarse fragments. Changes in the subsoil properties which affect soil productivity include: mechanical strength, aeration porosity, water storage porosity, residual porosity, bulk density, permeability, and rooting depth. Reductions of 15 and 25 percent in inherent soil productivity are suggested as a basis for setting threshold values for measurable and observable soil properties or conditions based on current methods, technology and research.

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SOIL POROSITY AS AN INDICATOR OF FOREST AND RANGELAND SOIL CONDITION (COMPACTION) AND RELATIVE PRODUCTIVITY

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ABSTRACT

Management activities that disturb the soil alter its structure. Such structural changes may reduce plant productivity on altered soils. Soil compaction and puddling are prognosticative indicators of adverse soil structural changes. They indicate altered porosity and increased soil strength. These alterations affect root growth and function and thus plant productivity. Bulk density and cone penetrometer readings are common indices of soil porosity and soil strength. A combination of both provides a better indication of potential root growth and plant productivity than either alone. Soil penetrometers are useful reconnaissance instruments, because many data can be obtained in a short time. Bulk density data, however, are more reproducible by different instruments and methods with different soil moisture conditions. Therefore, bulk density or soil porosity should be the ultimate standard for assessing the soil structural affects of soil disturbance. Agencies that utilize a bulk density standard for soil condition need at least 2 limits - one for soils with particle densities near 2.65 Mg/m^3 and another for soils in volcanic ash that have much lower particle densities. With a soil porosity standard, only one limit serves better than the 2 or more values required with a bulk density standard. It is better, because with soil porosity the change required to exceed the standard value decreases as the porosity decreases toward more limiting bulk density. The proposed limit is a 10% reduction in soil porosity.

INTRODUCTION

Plant growth is dependent on adequate supplies of water and nutrients. Vascular plants acquire the bulk of these necessities from the soil, through their roots. Roots function best when soil pores contain both readily available water and oxygen (Russell, 1977). Soils with favorable porosities and pore-size distributions have many capillary pores to hold plant available water and sufficient larger macropores to supply adequate air to the roots.

Forest and rangeland management activities that disturb the soil alter its structure and thus its capacity to hold plant available water and supply oxygen to plant roots. These structural alterations and accompaning increases in soil strength usually, but not always, have adverse affects on root growth and plant productivity.

Our objective is to summarize the effects of soil compaction on productivity in forest and rangeland management and discuss means of assessing soil compaction that relate to its affect on plant growth.

DEFINITIONS

Particle Density. Solid particle density (Ds) is defined as weight (W) per volume of solid particles, Ds = W/Vs, where Vs is the volume of solid particles. It is equivalent to specific gravity when the units are g/cm^3 or Mg/m^3.

Soil Bulk Density. Bulk density (Db) is defined as weight (W) per total volume, Db = W/(Vs+Vv), where Vs is the volume of solid particles and Vv is the volume of voids (all space not occupied by solids).

Soil Compaction. Compaction is simply a reduction in volume. It generally occurs when stresses are applied to soils with sufficient magnitude to deform and compress them. Loose or saturated soils may compact from the force of gravity alone. Clayey soils may compact by contraction due to internal forces upon drying. We are concerned here with compaction due to external stresses from machinery and animal traffic.

Soil Pores. Soil pores are the spaces between solid particles in soils. They are characterized by their sizes, shapes (including tortuosity), and continuity. Water drains from continuous pores larger than about 0.030 mm in diameter at suctions > 10 kPa, which is commonly assumed to be "field capacity" (Dexter, 1988). Larger pores (diameter > 0.03 mm) might be considered macropores, although macropores are commonly considered to have diameters > 0.075 or 0.1 mm.

Soil Porosity. Soil porosity (P) is the volume of voids per total volume of soil, P = Vv/(Vs+Vv). Total porosity can be computed from bulk and particle densities by P = 1-Db/Ds. Soil porosity without specification of pore size generally refers to total porosity.

Soil Puddling. Soil is puddled when it is deformed by shearing. Soil deformed when saturated, which is common for puddling, may not be compacted unless the shearing occurs over sufficient time for some water to drain or be forced from the soil. Puddled soils with much active clay may compact upon drying.

MEASURES OF SOIL DISTURBANCE AND COMPACTION

Kinds of Disturbance

Logging, site preparation, trampling, and off-road vehicle traffic may cause soil displacement, soil mixing, soil compaction, and puddling (Gifford et al., 1977; Greacen and Sands, 1980; Miller et al., 1989; Scholl, 1989).

Soil displacement can be quantified as (1) the area from which soil or O-horizon was displaced, (2) the volume or mass of soil displaced, or (3) a combination of volume or mass and distance displaced. Rut depth is sometimes used as an indicator of puddling.

Determinations of soil mixing may be qualitative, simply indicating the horizons mixed, or quantitative, indicating the depth of mixing.

Soil compaction can be assessed in many ways (Table 1). It is commonly expressed in terms of soil bulk density, or increase in bulk density. Soil porosity, or decrease in porosity, is a more direct measure of soil compaction, because any reduction in soil volume is proportional to the reduction in porosity (any reduction in the volume of solid particles is negligible).

Table 1. Common methods for assessing soil condition in relation to soil compaction.

Soil Property	Method[a]
Bulk Density	cores
	clods
	irregular holes
	attenuation of gamma radiation
Strength	consistence, qualitative
	cone (static) penetrometer
	dynamic penetrometer
Structure and pore-size distribution and character	aggregate size and strength
	visual observations
	macroscopic
	microscopic
	permeability
	air
	water
	infiltration of water

[a] Plant root form and distribution can sometimes be used to assess soil condition.

Soil strength increases with compaction and puddling. Thus, soil strength is an index of soil condition related to soil compaction. There are many ways of measuring soil strength, but the usual ones in forest and rangeland soils are qualitatively with a spade or quantitatively by resistance to static penetration, commonly with a cone penetrometer.

Total porosity can be computed from soil particle and soil bulk densities. Productivity, however, may be more closely related to macroporosity. There are no practical field measures of macroporosity. Infiltration and permeability are good indices of favorable combinations of macroporosity and macropore orientation and continuity. Permeability can be determined with water, air, or gases other than air.

The compaction of aggregated soil is due primarily to the reduction of macropores between aggregates (Day and Holmgren, 1952; Gupta et al., 1989). As compaction proceeds, total porosity decreases in proportion to the reduction of macropores (macroporosity), until the aggregates are obliterated. Therefore, macroporosity has little advantage over total porosity as an indicator of the effects of soil compaction in forest and rangeland management. Macropore orientation and continuity, which are independent of macroporosity, are very important in the transmission of water and air; thus permeability has advantages over total porosity even though it is not a reliable predictor of macroporosity.

Undisturbed Soil Densities and Porosities

Soil compaction decreases porosity and increases the concentration of solid particles. Soil bulk density is a common field measurement. Soil porosity, however, being more difficult to measure, is generally computed from soil bulk density and particle density. This computation requires that solid particle density be measured or estimated. Estimates are generally satisfactory, but they require some knowledge of expected particle densities.

Solid particle densities range from about 1.4 Mg/m^3 for soil organic matter (Skempton and Petley, 1970) to 2.65 Mg/m^3 or greater for mineral and rock fragments (Daly et al., 1966). A solid particle density of 2.65 Mg/m^3, which is the density of quartz, is generally considered the mean unless the particle density is actually measured for a soil. Fresh pyroclastic rock fragments with occluded pores have much lower densities (Smith and Smith, 1985), but they soon revert to a mean of their mineral and glass components due to weathering in soils (Bielders et al., 1990). Volcanic glass densities range from 2.33 to 2.85 Mg/m^3 (Daly et al., 1966). Densities in this range are attained in 1700 years or less for inorganic particles in soils of New Zealand derived from pumice (Packard, 1957).

Soil bulk densities range from 0.07 Mg/m^3 (Silc and Stanek, 1977) or less (Lynn et al., 1974) in organic soils to 2.09 Mg/m^3 (Rawls, 1983) in inorganic soils. They are closely related (inversely) to soil organic matter contents (Alexander, 1989), primarily because soil porosity increases with organic matter content, rather than due to the lower particle density of organic matter (Fig. 1).

Soil porosities range from 0.21 (21%) in a inorganic soil with a bulk density of 2.09 Mg/m^3 to > 0.95 (95%) in organic soils with bulk densities < 0.07 Mg/m^3. Most inorganic soils have porosities between 0.4 and 0.7; they generally have more voids in their A-horizons and about equal amounts of solid particles and voids in compacted surface horizons and in subsoils.

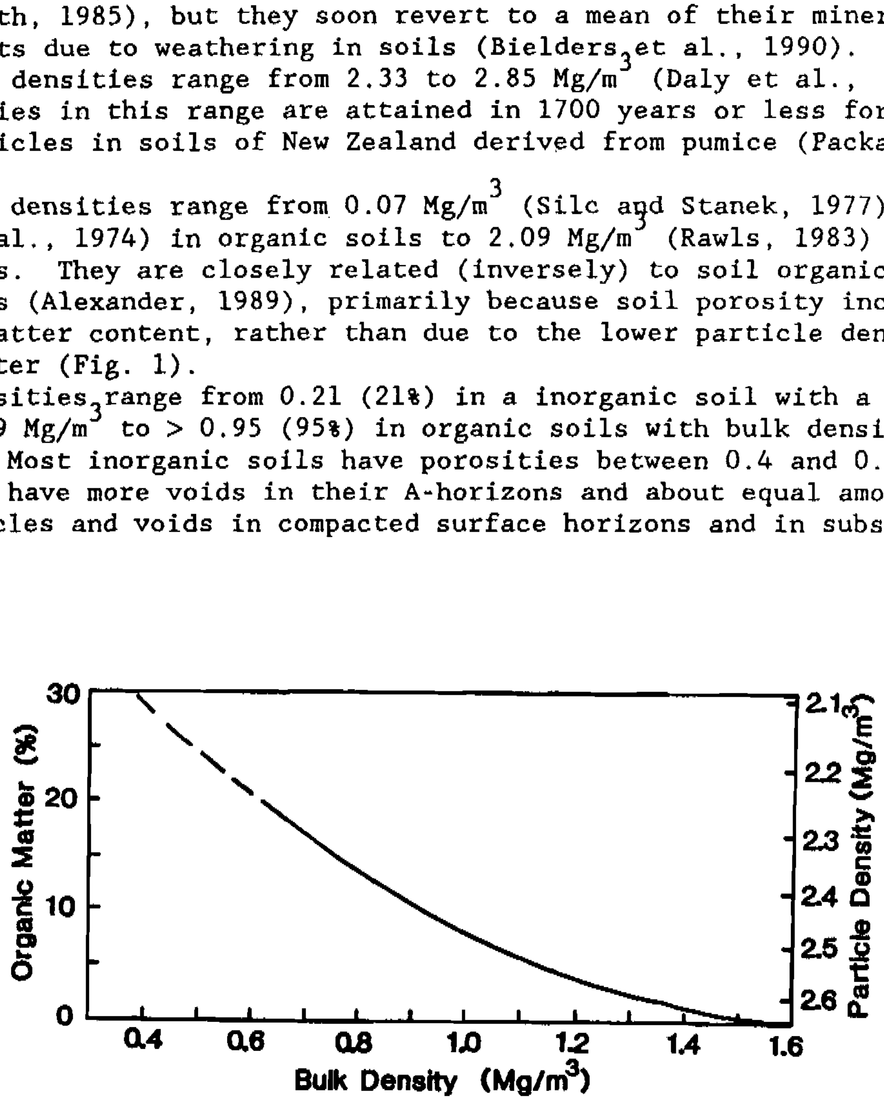

Figure 1. The effects of soil organic matter content on mean solid particle density and expected bulk density in uncompacted soil. Assuming inorganic and organic particle densities of 2.65 and 1.4 Mg/m^3, respectively, mean soil particle densities (Ds) were computed from $100/Ds = SOM/1.4 + (100\text{-}SOM)/2.65$ and soil bulk densities by $Db = 1.66\text{-}0.308\ (SOM/1.724)^{0.5}$ (Alexander, 1980), where SOM is the soil organic matter content (% by weight).

EFFECTS OF SOIL DISTURBANCE AND COMPACTION ON PRODUCTIVITY

Two aspects of soil disturbance affect plant growth: soil displacement and compaction. Clayton et al. (1987) measured disturbance in 3 tractor-logged clearcuts and found that reductions in conifer tree growth were associated ($p < 0.1$) with soil displacement and increased soil strength in all three clearcuts and highly correlated ($p < 0.01$) with increased soil bulk density in one of the clear cuts. There have been many reviews of the effects of soil disturbance (Alexander and Poff, 1985) and compaction on roots and plant growth (Greacen and Sands, 1980; Omi, 1986; Miller et al., 1989). Both bulk density and soil strength have been found to be reasonably good predictors of conditions that limit root system development (Thompson, et al., 1987) and shoot growth.

Reductions in tree growth are commonly related to relative increases in surface soil bulk density. Froehlich and McNabb (1984), for example, related reductions in tree growth to the relative (percent) increase in bulk density. This kind of comparison has prompted forest soil scientists to base guidelines for recognizing "significant" soil compaction on relative increases in bulk density.

Data from various sources (Duffy and McClurkin, 1974; Zisa et al., 1980; Helms, 1983) indicate that increases in bulk density of light (porous) soils have little or no effect on plant growth, but that comparable increases in bulk density of heavy (dense) soils have substantial effects on plant growth. Helms, for example, found relatively small decreases in ponderosa pine tree growth on Aiken loam with surface soil bulk density increases from <0.85 to 1.0 Mg/m^3, but large decreases in growth at 1.1 Mg/m^3 (Alexander and Poff, 1985, Table 10). On a Holland taxajunct with a sandy loam surface, ponderosa pine tree growth decreased slightly through 6 increments of bulk density increase, from 0.92 to 1.18 Mg/m^3, then growth decreased greatly with the next increase in bulk density to 1.27 Mg/m^3 (Alexander and Poff, 1985, Table 11).

The results of Helms, plus the possibility that tree growth might even increase with some compaction of soil with very low bulk density (Miller et al., 1989), suggest two possible thresholds, or discontinuities, in bulk density-plant growth relationships: one at the minimum bulk density for observing reduced plant growth upon compaction and another at the maximum (or limiting, Daddow and Warrington, 1983) bulk density for root penetration. Even in soils where these thresholds are not recognized, the bulk density-plant growth relationship is unlikely to be linear approaching the suggested limits which might be thresholds. Short segments of a bulk density-plant growth curve may appear linear, but there is generally so much "noise" in field data that the shape of the curve cannot be determined unequivocally.

ASSESSING SOIL COMPACTION

Three methods of assessing soil compaction are sufficiently popular to warrant further discussion: cone penetrometers (soil strength), bulk density, and the Steinbrenner air permeameter (Steinbrenner, 1959; Alexander and Poff, 1985).

Comparison of Methods

Cone penetrometer and Steinbrenner air permeameter readings can be made very quickly (Gifford et al., 1977), but they are more difficult to interpret than bulk density. Penetrometer reading can be converted to stress (or pressure), but the results depend on cone size and angle, soil water content, and rate of penetration (Fritton, 1990). Steinbrenner air permeameter readings are independent of water content in soils drained to "field capacity"; however, they are dependent on pore sizes, orientation, tortuosity, and continuity. Air permeameter readings are poorly, but significantly, related to surface soil porosity (Alexander et al., 1985), although the relationship is very good for sieved soil (Alexander and Poff, 1985).

A practical strategy in monitoring compaction in managed units is to first make many penetrometer or air permeameter readings to locate areas of compaction and then to make a few bulk density determinations to characterize the conditions in uncompacted and compacted areas.

Soil Porosity vs Bulk Density for a SQS

Soil quality standards (SQS) are soil conditions of unimpaired, or insignificantly impaired, productivity. Representatives of some agencies have proposed a SQS for soil compaction based on bulk density, setting the limiting (or "threshold") condition at a bulk density increase that is expected to result in measurable productivity loss. We propose soil porosity as a much more satisfactory SQS for compaction.

A SQS based on relative increase in bulk density allows greater absolute increases in bulk density for soils of higher bulk density than for soils of lower bulk density. For example, a 15% bulk density increase from 1.0 to 1.15 is an absolute increase of 0.15 Mg/m^3 and a 15% increase from 1.4 to 1.61 is an absolute increase of 0.21 Mg/m^3 (Table 2). It seems more reasonable to allow absolute increases in bulk density which are smaller for soils of higher bulk density and larger for soils of lower bulk density.

Table 2. Comparisons of porosity decreases and bulk density (Db) increases, assuming a particle density of 2.65 Mg/m^3.

Initial Bulk Density	15% Db Increase			10% Porosity Decrease		
	Db Change		Porosity Change	Db Change		Porosity Change
	Abs.	Rel.		Abs.	Rel.	
Mg/m^3	Mg/m^3	%	%	Mg/m^3	%	%
0.6	0.09	15	-4	0.20	33	-10
1.0	0.15	15	-9	0.16	16	-10
1.4	0.21	15	-17	0.12	9	-10

If plant growth is the major concern in establishing guidelines (or standards) for soil compaction, relative bulk density increases are unsuitable criteria. The increments of acceptable increase should become smaller in absolute value as the bulk density increases. This would be accomplished by basing the allowable increments on decreases of soil porosity rather than on increases of bulk density (Fig. 2). An allowable decrease of 10% appears reasonable. A 10% decrease in porosity would be the same as a 15% increase in bulk density for a soil with an initial bulk density about 1.0 Mg/m^3 and a 20% increase for a soil with an initial bulk density about 0.8 Mg/m^3 (Fig. 3). This eliminates the need for a special rule for Andisols and other soils with low particle and bulk densities.

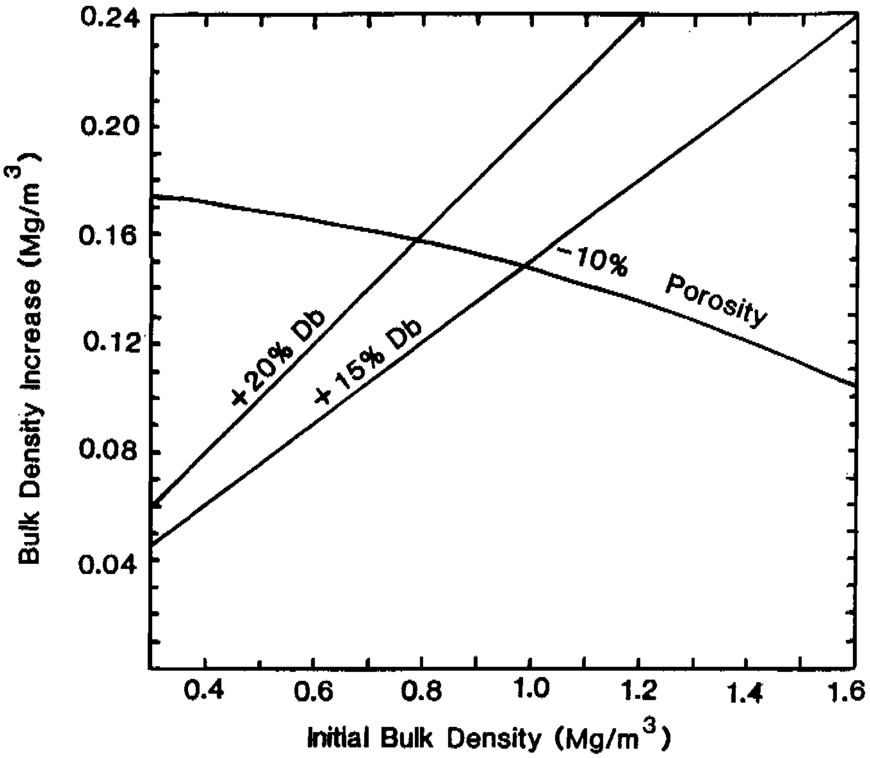

Figure 2. Absolute increases in soil bulk density corresponding to 15% and 20% increases in bulk density and a 10% decrease in soil porosity.

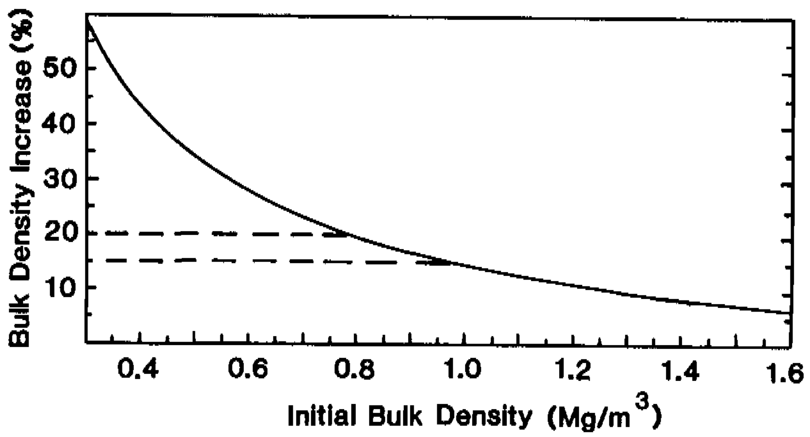

Figure 3. The relative increase in soil bulk density, labeled "bulk density increase", corresponding to a 10% decrease in soil porosity.

The initial soil bulk density must be measured. Then the allowable compacted bulk density, based on a 10% decrease in soil porosity, can be calculated by

$$Db_c = 0.1\ Ds + 0.9\ Db_i$$

where Ds is the mean solid particle density and Db_i and Db_c are the initial and the compacted bulk densities, respectively. Assuming that the particle density is 2.65 Mg/m^3, the allowable compacted bulk density can be taken from the solid line in Figure 4. Making allowances for soil organic matter, which has a density of about 1.4 Mg/m^3, has little effect on the calculated allowable compacted bulk density of inorganic soils (dashed line in Fig. 4).

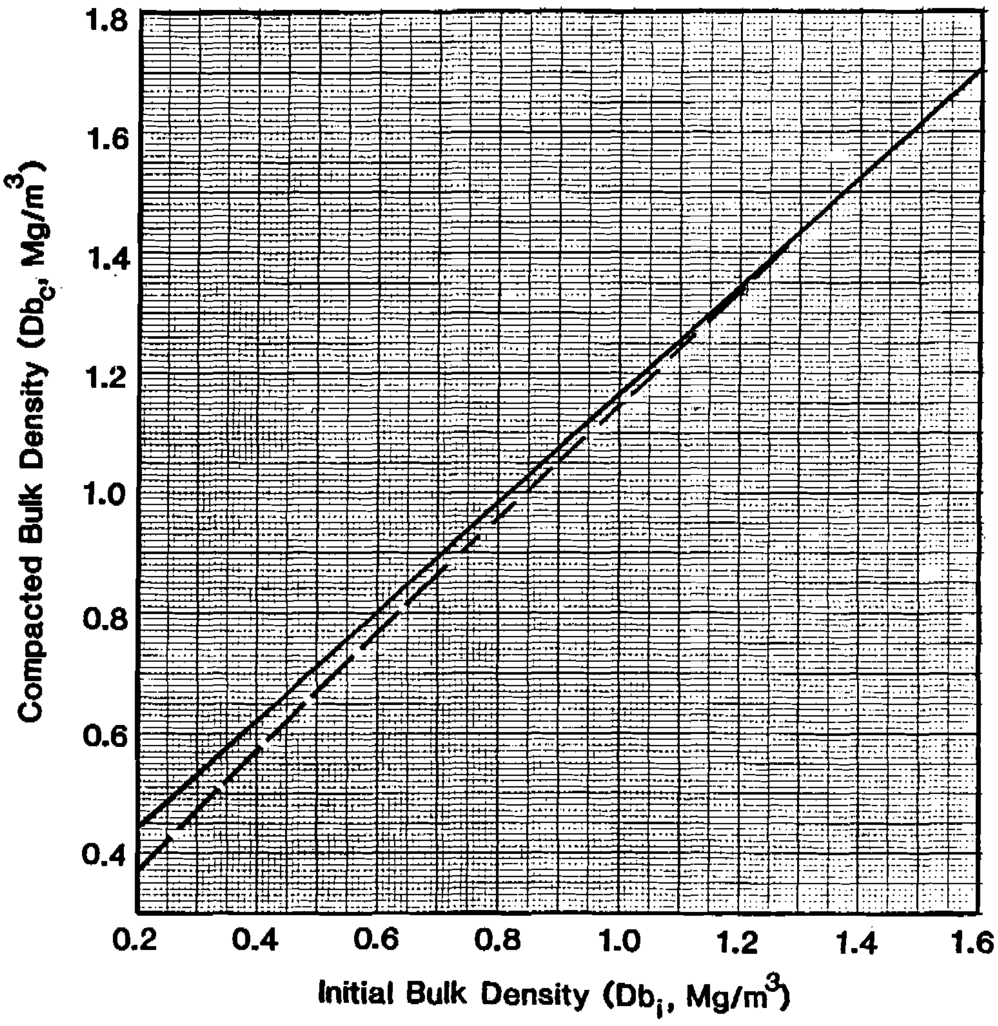

Figure 4. Compacted soil bulk densities corresponding to a 10% decrease in soil porosity. The solid line represents an inorganic particle density of 2.65 Mg/m^3 and the dashed line represents a mean particle density resulting from a mixture with organic matter. The percentage of soil organic matter (SOM) for initial bulk densities was estimated from the equation $SOM = 18\ (1.66-Db)^2$, which is a transformation of the equation presented in Figure 1.

CONCLUSION AND RECOMMENDATIONS

Soil compaction and puddling are indicators of adverse soil structural changes such as altered porosity and increased soil strength. Bulk density and cone penetrometer readings are common indices of soil porosity and soil strength. Cone penetrometers are useful reconnaissance instruments, because many data can be obtained in a short time. Bulk density data, however, are more reproducible by different methods and with different soil moisture conditions. Bulk density is a more basic standard for assessing the soil structural affects of disturbance. The standard limit is generally considered to be a relative (percent) change that is expected to cause a measurable reduction in productivity. Soil porosity, computed from bulk and particle densities, is a more satisfactory standard, because (1) the same limit can be applied to all soils, regardless of composition, and (2) the absolute change exceeding a standard limit decreases as the porosity decreases toward more growth limiting density. The proposed limit is a 10% reduction in soil porosity.

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SOIL PARAMETERS SIGNIFICANT TO PESTICIDE FATE

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ABSTRACT

Soil properties have both direct and indirect effects on the fate of pesticides that are applied to the soil or otherwise reach the soil after application. These soil properties may affect retention within the profile, transport through the profile, and/or transformation within the profile. The fate (retention, transformation and transport) of pesticides is determined by the interaction of pesticides, climatic variables, soil properties, and biotic activity within the soil profile. While these interactions are subtle, processes have been identified and published by researchers that describe the dynamics of the environmental fate of pesticides.

INTRODUCTION

Soil properties significantly affect the fate of pesticides in the environment. Consideration of soil parameters that control or mediate the behavior of pesticides relative to efficacy or environmental fate is a necessary step in pesticide stewardship. The behavior of pesticides in soil systems can be described in terms of their retention (sorption), transformation (degradation), and transport (movement) in the soil system. Several books and book chapters have been written describing the behavior of pesticides and other organic chemicals in soils (Cheng, H.H., 1990; Haque and Freed, 1975; Grover, 1988; Gardner, Honeycutt, and Nigg, 1986; Hern and Melancon, 1986; Cheng and Koskinen, 1986; Helling and Gish, 1986) and many journal articles document individual research efforts elucidating the processes that determine the fate of pesticides in the soil environment. This paper will attempt to provide an overview of some of these findings to illustrate the role of soil properties with respect to fate of pesticides in soils.

RETENTION PROCESSES

Retention of pesticides in soils has been described by sorption processes such as partitioning into the organic carbon fraction of soils, ion exchange, and physical adsorption. The equation commonly used to describe this phenomenon is as follows:

$$K_d = K_{oc} + K_{exc} + K_p$$

where K_d represents the ratio of pesticide adsorbed on a particular soil to the pesticide concentration in the soil solution at equilibrium; and K_{oc}, K_{exc}, and K_p represent the contributions due to partitioning into the organic carbon fraction of soils, ion exchange, and physical adsorption by van der Walls forces. Thus, organic matter content of soil acts as a capacity factor in determining the amount of pesticide sorbed, the greater the organic matter content the greater the amount of pesticide that can be sorbed. For example, muck and peat soils have high retention capacities for pesticides.

Sorption occurs on mineral surfaces by adsorption. Hance (1988) has described adsorption-desorption processes occurring on soil colloids. He categorizes these processes into high-energy bonding and low-energy bonding. High-energy bonds include ion exchange and ligand exchange. Soil colloids including both clays and organic mater exhibit charged surface sites with which ionic pesticides interact. Most soils contain clay minerals with net negative surface charges providing exchange sites for cationic pesticide. Examples of cationic pesticides are the herbicides paraquat and diquat. Some soils such as Oxisols contain metal oxides that exhibit a positive surface charge, thus providing exchange sites for anionic pesticides.

Since some pesticides are ionic or ionizable, ion exchange capacity of the soil is an important soil parameter affecting the fate of pesticides in soil. Due to acid (pK_a) or base (pK_b) dissociation constants, ionizable pesticides may be in molecular form in certain soil pH ranges and ionic form in other soil pH ranges. Thus soil pH becomes a relevant soil parameter in assessing environmental behavior of pesticides, as it affects the degree of retention in soils.

Ligand exchange is another high-energy bonding mechanism by which some pesticides may be bound to chelated transition metals on clays and humic acids in soils. This mechanism has been suggested for triazines, substituted ureas, amitrol and EPTC.

Adsorption by low-energy bonding includes: hydrogen bonding, charge transfer, charge-dipole and dipole-dipole bonding, and London-van der Walls forces. The degree to which these mechanisms contribute to pesticide retention in soil is related to the specific surface area of soil colloids. Soils with high specific surface areas exhibit greater physical adsorption than those with low specific surface areas.

Three other phenomena affect retention of pesticides in soil. First, some soils act as molecular sieves, trapping volatile pesticide molecules within pores. The pesticide molecule becomes physically trapped in the pore structure of soil aggregates preventing its further movement by diffusion or advection. Second, during biodegradation some fraction of the pesticide becomes "bound residue" that cannot be extracted by conventional extraction methods. The form and bioactivity of the bound residues are unknown but are known to occur as evidenced by mass balance determinations. And third, some pesticides are adsorbed at the air-water interfaces of water-unsaturated soils: thus soil-water content is a factor to consider in understanding retention processes.

Koskinen and Harper (1990) have published an excellent review of the retention mechanisms and methods to determine retention mechanisms. They concluded that retention processes control all other processes in soil that affect pesticide fate and that in order to understand how the retention processes interact with other processes, the retention mechanisms must be known.

A summary of the soil parameters that affect pesticide retention in soil is given in Table 1. Capacity parameters are those soil parameters that account for the degree of retention of pesticides in soil and intensity parameters are those that affect the rate at which retention processes proceed. In some instances a parameter may function as a capacity and/or intensity parameter. In Table 1 temperature and soil water content are shown in both columns. Temperature mediates the rate of reaction of sorption processes in soils and well as limiting the amount of sorption. Soil-water content affects sorption at air-water interfaces at certain relative humidities. Although not included in column 1 of Table 1, soil pH might also be considered as having a dual role; the amount of ionizable pesticide sorbed would depend on ambient soil pH and pK_a and pK_b values.

Table 1. Soil parameters affecting pesticide retention in soils.

Capacity parameters	Intensity parameters
Organic matter content (organic carbon content)	Temperature
Ion exchange capacity	Soil reaction (pH)
Type and amount of clay minerals (surface area)	Soil-water content
Metal oxide content	Bioactivity (bound residues)
Pore size distribution	
Soil-water content	
Temperature	

TRANSFORMATION PROCESSES

Transformation of pesticides can be considered mediated by two different driving forces, biological (biotic) and non-biological (abiotic). Abiotic processes include chemical or photochemical pathways of degradation in or on the soil surface. Abiotic reactions may range from simple hydrolysis or oxidation to catalysis by metal oxides or organic matter in the soil.

Abiotic Transformations

Processes of abiotic transformation have been described in detail by Valentine (1986) and Wolfe, Mingelgrin and Miller (1990). Chemical hydrolysis, oxidation-reduction and photochemical transformation mechanisms and kinetics are described. Soil parameters relevant to abiotic transformations are given in Table 2. As was the case with retention processes, some soil parameters occur as both capacity and intensity factors. Hydrogen ion concentration (pH) can affect chemical hydrolysis rate in several ways. The rate of the acid-promoted process is a function of hydrogen ion concentration. The soil pH affects ionization of the chemical in the soil and the amount of chemical adsorbed by the soil.

Components of soil organic matter are known to catalyze the hydrolysis of organophosphate esters.. Soil organic mater contains both potential oxidizing and potential reducing agents. The presence of organic matter may affect soil oxygen concentration through increased microbial activity and thereby indirectly affect the rate of oxidation or reduction.

Biotic transformations

Biodegradation of pesticides in soils has been studied widely to understand efficacy of products with respect to duration of control. More recently the emphasis has been on understanding persistence as it may affect environmental quality. The basic principles of pesticide degradation in soil are reasonably well known and have been described by numerous researchers, including Goring et al. (1975), Valentine and Schnoor (1986), and Bollag and Lui (1990). Soil microbes are ubiquitous and many are effective in breaking

Table 2. Soil parameters affecting abiotic transformations of pesticides in soils.

Capacity parameters	Intensity parameters
Metal oxides/ions	Temperature
Oxygen status	Water content
Soil reaction (pH)	Soil reaction (pH)
Organic matter	
Water content	
Clay content	

down pesticides into various degradation products and in some cases to CO_2 and water. Their effectiveness depends on several factors, some of which relate to soil properties. Table 3 contains a list of soil parameters relevant to biotic degradation of pesticides in soil systems. Soils serve as the environment in which water, heat, oxygen, and nutrients are provided to soil microbes. These inputs interact to determine the efficacy by which microbes degrade pesticides in soil.

Organic matter and associated nutrients provide energy for microbial metabolism. Presence of oxygen in the soil affects the mechanism and rate of microbial degradation. Sorbed pesticides may not be available for intracellular degradation as has been shown by Weber and Coble (1968) and Ogram et al. (1986).

Ou et al. (1982) demonstrated differences in degradation rates of carbofuran at differing soil temperatures and soil moisture contents for soil samples taken from widely separated locales in the United States. In Figure 1 we see the effects of varying soil-water pressure on disappearance of carbofuran in five soils at 27 degrees Celsius. While slight changes occurred between -0.1 and -1.0 bar soil-water pressure, marked change in rate of transformation occurred only between -1.0 and -15 bar soil-water pressure. The effect of change in temperature on rate of transformation of carbofuran in four soil samples held at -0.33 bar soil-water pressure is shown in Figure 2. The data show that degradation rate was reduced (half-life increased) at 15 C compared to the rates at 27C and 35C for the Webster soil from Iowa, and the Cecil soil from Georgia. The other soil samples, Sharpsburg from Nebraska and Houston from Arkansas, showed increased degradation (half-life decreases) rates between 24 C and 35 C . These figures attest to the complex interrelationships between soil parameters and biotic transformation of pesticides in soils.

TRANSPORT PROCESSES

Understanding the transport of pesticides through soils is necessary in considering assessment of efficacy as well as water quality impacts of pesticide use. Transport through soils may occur in the gas or liquid phase. Furthermore, the driving forces may be either, or a combination of, diffusion in response to concentration gradients and mass flow by advection (carried by water, air, or other fluids). Sorption of pesticides in soils retards their movement through the soil matrix. Transformations reduce the mass emission of pesticides in the leachate by degradation or tieup of the pesticides in the

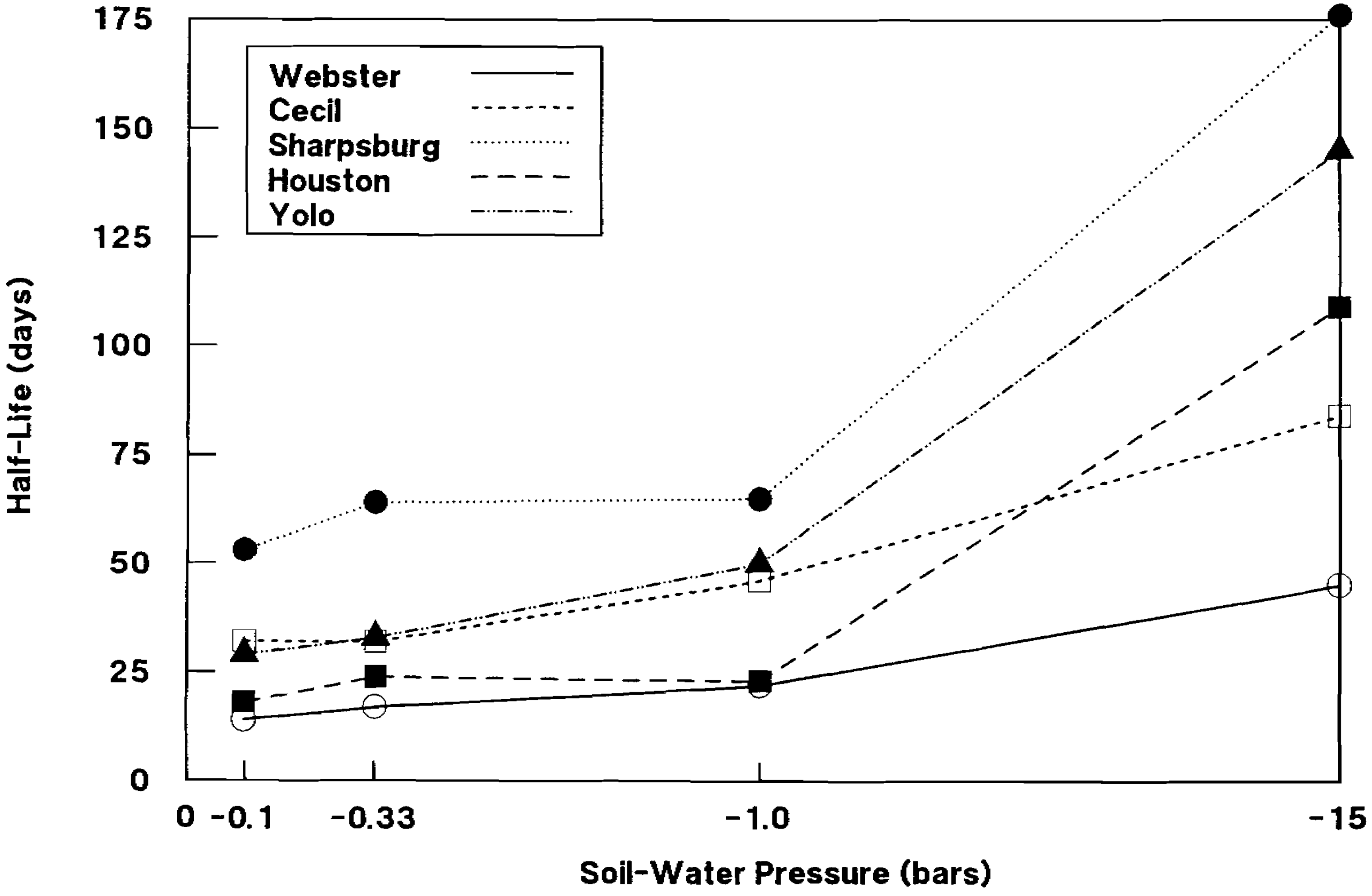

Figure 1. Effect of soil-water pressure on transformation rates of carbofuran in soils held at 27 C (adapted from Ou et al., 1982).

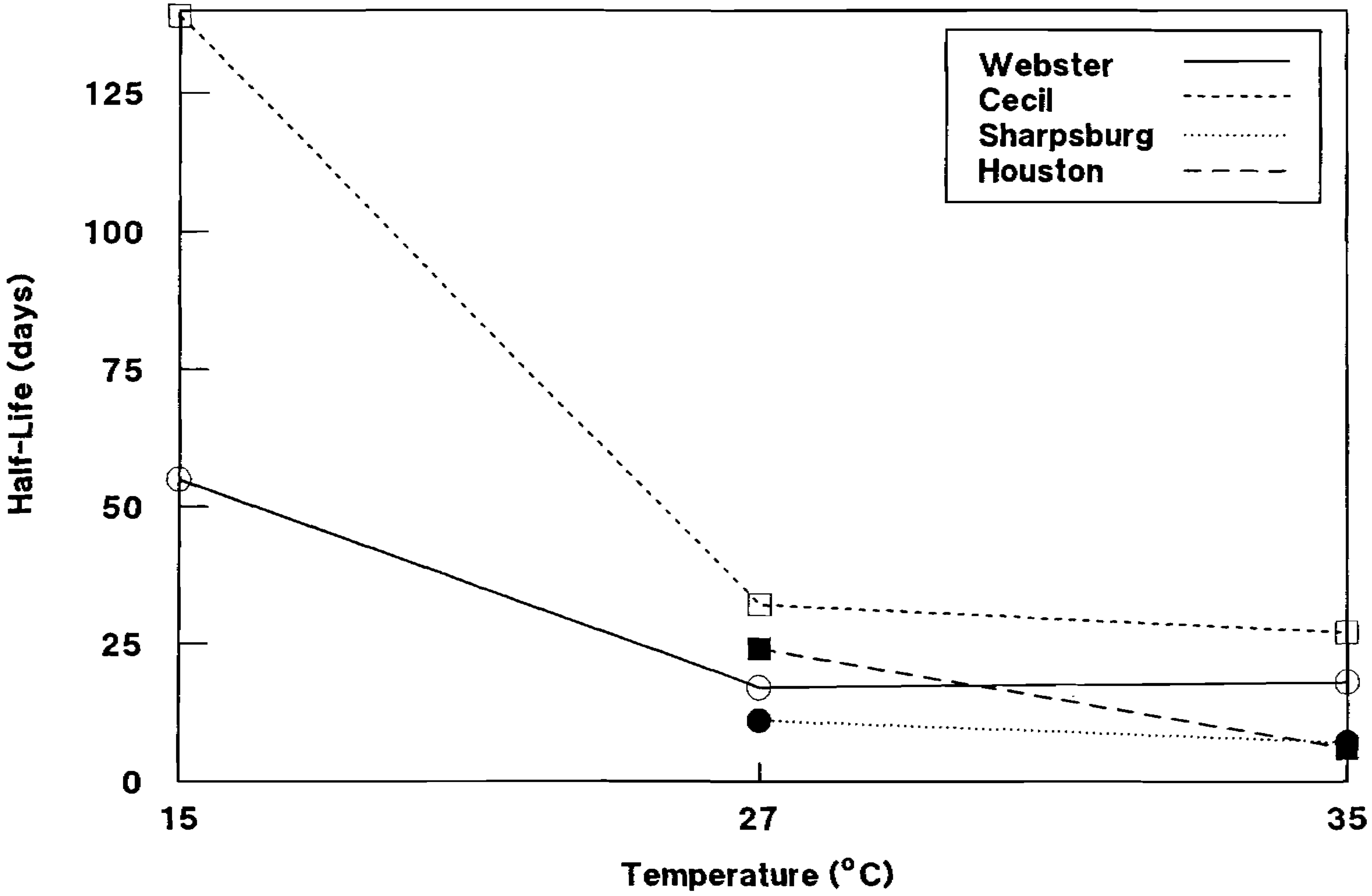

Figure 2. Effects od soil temperature on half-lives of carbofuran in soils held at 0.33 bar soil-water pressure equivalent (adapted from Ou et al., 1982)

Table 3. Soil parameters affecting biotic transformations of pesticides in soils.

Capacity parameters	Intensity parameters
Bioactivity (population and diversity)	Temperature
Oxygen status	Water content
Soil reaction (pH)	Soil reaction (pH)
Organic matter	
Water content	
Clay content	
Substrate (nutrient source)	

soil biomass. Rao, Jessup and Davidson (1988) have described the principles governing transport of pesticides by soil water. Gas phase transport was well described by Taylor and Glotfelty (1988). An review of both aqueous and gaseous phase transport by Jury et al. (1987) integrates transport in the two phases with transformations.

Soil factors that affect the pesticide transport in soil include those that affect fluid (air and water) flow as well as those that affect sorption and degradation processes since transport is an integration of all these processes. Clay type and saturating ion can interact to affect the permeability and hydraulic conductivity of soil, thus affecting liquid phase pesticide transport. Air-filled porosity is one of the controlling factors affecting gas-phase transport. Pore size distribution and soil-water content interact to determine the air-filled porosity.

Table 4. Soil parameters affecting transport of pesticides through soils.

Capacity parameters	Intensity parameters
Clay content and type	Temperature
Porosity	Water Content
Bulk density	Hydraulic Conductivity
Organic matter	Saturating ion
Ion exchange Capacity	

ADDITIONAL CONSIDERATIONS

It will be noted that most of the capacity/intensity parameters affecting pesticide retention, transformation, and transport can be and in fact must be quantified if their role is to be known well enough to effect prediction of pesticide fate. Note also that some--though not all--of the parameters are known for many soils through soil survey and soil characterization work. Often, however, soil survey/characterization findings are insufficiently quantitative to allow the prediction of pesticide behavior without making chancy and perhaps unwarranted assumptions about the occurrence and especially the variability of soil attributes in the landscape. This gap in our knowledge is all the more frustrating when we consider that the degree of soil variability and the structure of soil variability are two soil features that rival the parameters listed above (Tables 1-4) in their control of pesticide fate in the environment. Such deficiency in our knowledge of the soil landscape is no one's fault; the landscape is very complex and does not lend itself easily to quantification. The challenge for soil scientists is therefore not to assign blame for incomplete knowledge of the soil. Rather, the task is to undertake cooperative, quantitative study of the landscape, with view to better understanding of the composition of soil map units and of the quantitative behavior of soils as they occur in interaction with the landscape of which they are a part (Bouma, 1986; Brown and Huddleston, 1991; Hillel, 1991; Stein et al., 1988).

SUMMARY

Soil properties interact in a dynamic manner to affect the behavior of pesticides in soil environments. Whether the issue is efficacy, environmental quality or soil quality (in the sense of how clean is clean) the soil based processes that determine the fate of pesticides and other toxic chemicals are the same. Soils are active biological and chemical reactors that serve the ecological community very well as a storehouse of nutrients, and moisture, as well as a matrix for plant growth, and as an interface between terrestrial activities and groundwater quality. Understanding how soil properties interact to accomplish these roles is imperative in maintaining the quality of life that our society has come to expect.

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SUSTAINING SOIL QUALITY BY PROTECTING THE SOIL RESOURCE

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INTRODUCTION

People depend upon soils to meet a variety of societal and human needs such as the production of food and fiber. Soils also are important in the hydrologic cycle storing water for plant growth and purifying drinking water by percolation. Humans use soil to stabilize and store human wastes, reducing exposure to disease and other hazards.

Even though soils are an important resource they are generally overlooked and their chronic loss and degradation goes unnoticed. Soil is continually being lost by wind and water erosion, or rendered unusable and unproductive by chemical and physical degradation. Rates of soil loss caused by human activities are greater than rates of replacement. If this loss and degradation continue while the demands of an increasing world population go unabated a point will be reached where the demands placed on soils will go unmet. To forestall reaching this point we discuss the potential of protecting soils specifically as a critical resource. We also propose an initial framework to sustain soil abundance, quality, and productivity for future generations.

BACKGROUND

Soils are a complex mixture of minerals, gases, water, and organisms, taking hundreds to thousands of years to form. Once lost or degraded soil is not easily replaced or restored. The supply of productive soils is getting smaller every day. The annual loss of soil due to erosion on croplands alone is estimated to be about 24 million metric tons (Brown and Young, 1990). Additionally, soils are lost to urbanization, road building, and development. A common misunderstanding is that society can permit soils to be misused because the supply of soil is virtually unlimited, and soils that are lost or degraded can be replaced. This of course is untrue; the supply of soil is finite.

In 1990 the world's population was about 5.3 billion (Brown, 1990). In 2000 it is estimated to reach 6.3 billion, an average annual increase of 100 million people in the nineties. Demand for food and fiber increases in proportion to world population. Concomitantly, arable land per capita is decreasing. In 1990, of the 13 billion ha of land surface area (World Resources Institute, 1990a), 1.5 billion ha were in cropland, 3.2 billion in permanent pasture, 4.1 billion in forest and woodland, and 4.3 billion are classified as "Other Land." In 1955 per capita cropland was 0.5 ha (Blaikie and Brookfield, 1987). In 1989 it was 0.28 ha, and it is projected to be 0.17 ha in 2025 (World Resources Institute, 1990b). Because of technological advances food and fiber production have kept up with demand, even though per capita cropland decreasing. This trend cannot, however, continue. In addition to arresting world population growth, soil degradation and loss needs to be reduced.

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DEFINING SOIL QUALITY

Soil quality is not easily defined. To a farmer it may be defined in terms of fertility and tilth. To a forester it may be defined in terms of site classification. Because of soil spatial variability both of these are difficult to define quantitatively. One way of defining the soil quality, or rather the loss of soil quality, is in terms of soil degradation. Net soil degradation is the amount of degradation decreased by the amount of soil formation or restoration (Equation 1):

$$\text{Net Soil Degradation} = [\text{degradation - restoration}] \qquad [\text{Eq. 1}]$$

This definition has been expanded by Blaikie and Brookfield (1987). They defined net soil degradation as being equal to the sum of natural degradation processes plus anthropogenic degradation, minus natural soil formation plus restoration management (Equation 2):

$$\begin{aligned}\text{Net Soil Degradation} = {} & (\text{natural degradation} + \text{anthropogenic degradation}) \qquad [\text{Eq.2}] \\ & - (\text{soil formation} + \text{restoration management})\end{aligned}$$

This definition recognizes that there are two forces that can act to degrade soils, natural and anthropogenic processes, and that natural soil formation processes and management activities that can work together to reduce net soil degradation. If we use net soil degradation as a metric for soil quality, then soil quality declines when there is net degradation or increases when there is restoration. Conceptually this model is simple. It is, however, much difficult to quantify soil quality on an absolute scale particularly over large land areas.

Desertification is a form of land degradation that is generally associated with arid lands. Yet the definition (listed below) of desertification by Dregne (1983) is also applicable to non-arid lands and is well suited to our conceptualization of soil quality and provides some insights for quantification.

> "Desertification is the impoverishment of terrestrial ecosystems under the impact of man. It is the process of deterioration in these ecosystems that can be measured by reduced productivity of desirable plants, undesirable alterations int he biomass and the diversity of the micro and macro fauna and flora, accelerated soil deterioration, and increased hazards for human occupancy." - Dregne, 1983

CHARACTERIZING THE LOSS OF SOIL QUALITY

The loss or decline of soil quality can be caused by a variety of forces. The effects of these forces are evidenced by changes in either the physical, chemical or biological properties of the soil system.

Physical degradation

Physical degradation includes the following: the sealing and encrusting of topsoil; loss of the soil resource through physical erosion (wind or water) and compaction, that is the increase in soil bulk density usually due to heavy equipment being run over soils when they are wet. Compacting soil can produce had pans and reduce air pore space making it difficult for plant roots to penetrate or for oxygen to diffuse through. Physical degradation can also be a change in the hydrologic properties of the soil which stems from compaction or erosion, and reduces the soils water-holding capacity, infiltration, and/or permeability. Dispersion of aggregates is another form of physical degradation that can be caused by salts in irrigation water (chemical degradation). Waterlogging–that is water standing in the soil profile, prevents oxygen from freely diffusing in and out of the root zone, thereby making it difficult for plants to root. Desertification is another form of physical degradation, as is subsidence of organic soils, which is often associated with draining wetlands.

Chemical Degradation

Typically, when we think of the chemical degradation of soils, we think of hazardous wastes and Superfund sites. Even though the loss of soil quality does result from toxic or hazardous chemicals being applied, spilled, or leaked in or on soils, these systems represent an acute form of chemical degradation. There is a chronic form of chemical degradation that is more pervasive and potentially more damaging than the acute form. This is the slow, unseen degradation of soils caused by the long-term use of pesticides, fertilizers, and even irrigation water used to meet food and fiber demands.

Chemical degradation includes the loss of plant nutrients. Nutrients can be lost by overharvesting, by the application of inappropriate amounts of fertilizer, and by changes in soil pH due to fertilization with acid-producing fertilizers such as the ammoniacal forms of nitrogen. This effect is often rectified by the application of agricultural lime. However, soil acidification caused by acid deposition in some forests, is not readily corrected because lime cannot be easily applied and incorporated into the soil. Salanization is another form of chemical degradation. Salinization (i.e., increased salt content of soil) usually occurs in arid lands with the application of irrigation water where evaporation exceed infiltration. Salts accumulate at the soil surface creating a poor rooting environment.

The use of herbicides, insecticides, and other pesticides may alter or destroy natural food webs that commonly occur in soil. Organisms in these webs fix nitrogen and decompose plant material, which supply essential plant nutrients. Without these organisms, chemical nutrient replacements are required. The formation of anaerobic soil conditions by inundation above a tillage-pan can alter the soil chemical environment and can cause the toxic forms of some metal ions to become more abundant. The loss of soil organic matter is another form soil chemical degradation. Soil organic matter is an important soil constituent because it serves as a reservoir of plant nutrients, it has important water-holding characteristics, and exchange sites for nutrients.

Biological Degradation

Biological degradation is becoming more apparent as research in this area continues. Natural soils are rich in biodiversity, a loss of this diversity is one kind of degradation (Perry and Maghembe, 1989; Perry et al., 1990). For example, the loss of food web components can result in break-down in the rates decomposition and nutrient cycling; the use of herbicides and pesticides can selectively remove flora or fauna. Fungi are important for the development of macro-aggregates in soils which are important for good soil structure. Fungicides, herbicides, and other chemicals can eliminate these organisms that are important for maintaining soil tilth and productivity. Biological degradation or the loss of biological diversity can result intensive use of mono-cultures in agriculture and forestry. For example, forest plantations that are routinely harvested but kept in mono-culture will have diminished biological richness as compared to natural forest soils (Perry et al., 1990).

MEASURES OF SOIL DEGRADATION

For many years the extent of soil loss and degradation went unquantified. With the "dust bowl" of the thirties, the need to characterize soil loss and the factors that contribute to it became painfully apparent. Since then the US Department of Agriculture has engaged in a program to quantify soil loss due to erosion and to develop methods for preventing loss. Programs have also been developed to identify lands that are susceptible to erosion and providing incentives to remove these lands from agricultural production.

Recent research sponsored by the United Nations Environmental Program (UNEP) was designed to assess the extent of human-induced soil degradation. The program, called the Global Assessment of Soil Degradation (GLASOD), has the immediate objective of "strengthening the awareness of policy-makers and decision-makers of the dangers resulting from inappropriate land and soil management, and leading to a basis for the establishment of priorities for action programs" (Oldeman et al. 1990). It has produced maps of the status of human-induced soil degradation for the world. A compilation of the results is provided in Table 1. The extent of human-induced degradation of soils appears to be great, affecting more than 15% of the earth's land surface area. Without protecting the soil resource, food production and environmental problems are likely to be extensive.

FORMALIZING SOIL PROTECTION

In the United States, the Clean Air Act is aimed at protecting air resources in the U.S. from pollution. The Clean Water Act ensure that we will have high quality drinking water for decades to come. Both of these Acts came about because both of these resources can obviously be polluted. For instance, in the Los Angeles basin, heavily polluted air is clearly visible to a lot a people. People do not like to see what they are breathing. Therefore, the Clean Air Act was a logical conclusion. The Clean Water Act came about under similar circumstances when the water became so polluted that fish were dying and the water became unsuitable for drinking or recreation; then, legislation was developed to protect these resources.

The question becomes whether or not a "Clean Soil Act" is needed to insure that soils are adequately protected? If we value this resource, legislation specifically protecting soils may be necessary. To date, there is no Federal legislation that is specifically aimed at protecting soils. The Clean Air Act and the Clean Water Act provide specific protection for air and water resources but not for soils, the medium that connects the two. If legislators conclude that laws are needed to protect soils, what form should they take? Should it be modeled after the legislation now protecting air and water or other relevant legislation?

Protecting Air and Water: A Basis for Protecting Soils?

The Clean Air and Clean Water Acts are landmark bodies of legislation that serve to protect air and water resources in the United States. Although soils are a markedly different media than air or water, the Clean Air and Clean Water Acts may provide useful models for developing specific legislation to protects soil resources.

The Clean Air Act originated in 1963 (Environmental Statutes, 1989). It was developed to prevent and control air pollution. It was designed to enhance the quality of air resources, and aimed at preventing significant deterioration of air quality. The Clean Air Act had provisions to establish clean air standards. The Clean Water Act of 1977 was designed to restore and maintain the chemical, physical and biological integrity of water resources. It was also designed to reduce water pollution, to provide a mechanism for treating water through wastewater treatment plants. It too includes provisions to establish pollution standards. The subsequent clean air and clean water standards are chemical criteria that set pollution limitations. In general terms, the standards are set such that human health is protected and the respective resources are not significantly degraded. The focus in on end-points (i.e., air and water) and not on the processes that degrade them. Other related legislation includes the Safe Drinking Water Act of 1974, the Resource Conservation Recovery Act of 1976, and the Comprehensive Environmental Response Compensation and Liability Act of 1980, also known as Superfund.

Quantitative Approach

A quantitative approach similar to the pollution standards of the Clean Air and Clean Water Acts can be used to protect soils. With this approach chemical, physical and biological measures, or standards, of soil quality are developed and used as guidelines for protecting soil quality. Soil pH or bulk density are examples of soil properties that can be quantified and used as criteria for specific soils. Because soils are very complex and cover a wide range of chemical and physical properties it would be difficult to develop a single set of soil quality standards for soils in the United States. It is, however, not an impossible task and could be patterned after the agricultural extension approach. Within each state the extension service has developed criteria for making fertilizer and other recommendations for agricultural production based upon extensive research. The quantitative approach to soil protection would be an expansion of that process. Research would be conducted to develop chemical criteria for soil protection. Then recommendations for soil treatment would be made using these criteria. Additionally, soil remediation guidelines for degraded soils could be developed. For example when the pH of an agricultural soil drops below 5, liming to raise the pH would be an appropriate remedial activity.

Critical Loading Approach

The critical loads approach is based upon the concept that soils are naturally buffered against degradation and can tolerate a certain amount of disturbance (physical, chemical, etc.) before a degradation or damage occurs. The amount of disturbance that can occur before the damage threshold is crossed is called the "critical load." The success of the critical loads approach depends upon the development of chemical, physical and biological thresholds of soil quality. The objective of the critical loads approach is similar to the quantitative approach in that the aim is the development of regulatory guidelines to protect soils. Conceptually the two approaches are different in that the critical loads approach is more integrated. In the critical loads approach, criteria would be based on the three elements of soil quality–chemical, physical and biological–and thresholds would consist of these in combination. Soils could be used or manipulated until a critical load or threshold was reached. If exceeded, then remedial guidelines would have to be followed to remedy the problem.

Soil Function Approach

A third approach for protecting soils, and the one we would like to emphasize here, is the soil function approach. Soil function can be defined as "the potential utility of soils in landscapes resulting from the natural combination of soil chemical, physical and biological attributes." For example, food, fiber and fuel production are soil functions. Another is the soil serving as a reservoir of plant nutrients and carbon. A third is water filtration/purification and storage. Another function of soils is being a conduit for groundwater recharge. Another is that soils have a waste storage and degradation function. Finally, soils also function in ecosystem stability and resiliency (Perry and Maghembe, 1989). Soils buffer ecosystems from dramatic changes during stress. Soil functions are all features upon which society in general depends, and so if we take a functional approach, we aim to protect and sustain those functions. For example, some soils are best used for food production. These soils could be identified and then the food production function would be protected on those soils. Incentives could be developed that reward good soil stewardship and improvement of soil functionality. By specifically identifying and protecting soil functions, soil quality would be preserved, sustained, and improved.

Dutch Approach

In the Netherlands a Soil Protection Act was legislated in 1987 (DeWalle, 1987; Moen, 1988). It emphasizes restoration of degraded soils, prevention of degradation, and includes a dynamic set of published reference values of soil quality. An important conceptual feature of the Dutch Soil Protection Act is what they call the multi-functionality principle: "The multi-functionality of Dutch soils should be conserved, or, where it has been disturbed, be re-established." What this means is that soils have several functions (e.g., grazing, cropland, aquifer recharge, etc.) and they should be used for those functions in such a way that does not degrade their multi-functionality. Where soils have been disturbed, steps must be taken to restore or re-establish them. By developing soil protection based upon this principal the Dutch have acknowledged the importance and utility of soils and the need for sustainable management.

IMPLEMENTING SOIL PROTECTION IN THE U.S.

The Dutch Soil Protection Act appears to be a good framework for development of a Soil Protection Act in the U.S. Even though The Netherlands is much smaller than the U.S. and soil protection may be easier to implement and monitor there, the concepts of their Soil Protection Act are transportable. In the functional approach to soil protection, single soil functions are protected. With a multi-functional approach, like the Dutch', a number of soil functions are protected simultaneously which broadens the scope of soil protection and leads to more comprehensive soil protection.

As with the Clean Air and Clean Water Acts, quantifiable soil standards would need to be developed to provide metrics of soil function status and health. These could be chemical, physical, biological or ecological criteria, but more likely would be a combination of all four. These criteria would, of course, have to be related to functionality, and from this framework, we would develop regulatory guidelines.

Included in our soil protection policy should be an emphasis on preventing soil degradation and loss. We should prevent the continued degradation of this resource. Additionally, provisions for restoration of degraded soils should be included. Any soil protection policy should emphasize long-term sustainability. As with other resources, we need to use soils as a resource with an eye to the future, not degrading or diminishing the functionality of the soil resource.

RECOMMENDATIONS

Soil is less of an obvious resource than air and water. Consequently, soil protection in the U.S. does not have an advocate per se. It is therefore unlikely that legislation protecting soils will become a reality without a concerted effort by soil science practitioners and policy makers. Increased public awareness of the value of soils and the collection and presentation of data on the status and future of soil resources in the U.S. will advance the development of a sound soil protection policy. Soil scientists should be leading the charge for protecting soils. They need to convincingly demonstrate why soil protection is important and work to develop an implementable soil protection policy. This will involve data collection, interpretation, and presentation to audiences outside the soil science community. The GLASOD (Global Assessment of Human Induced Soil Degradation) research is an example of one kind of data that strengthens the call for soil protection.

For implementing soil protection in the U.S. we believe that taking a "soil multi-functional" approach will lead to an ecologically sound, soil protection policy. The Dutch Soil Protection Act may serve as a good model for the U.S. Soil function and multi-functionality concepts need further development and methods developed for their quantification. Meaningful measures of soil quality (health, condition and function) need to be developed so that soil protection criteria can be formulated. There will be a need for relevant research to support a soil protection policy, and soil scientists from all facets of soil research will need to cross disciplines and work together.

Reiterating the theme of this paper, soils are a finite resource on which society is intimately dependent. Acting now to protect this resource will insure that there will be sufficient soils of known quality and functionality to support generations to come.

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Table 1. Global Human-Induced Soil Degradation (Millions of ha†)

	Severity					
TYPE OF DEGRADATION	Light	Moderate	Strong	Extreme	Total	%‡
WATER						
Loss of Topsoil	301.2	454.5	161.2	3.8	920.3	
Terrain Deformation	42.0	72.2	56.0	2.8	173.3	
Total	343.2	526.7	217.2	6.6	1093.7	(55.6%)
WIND						
Loss of Topsoil	230.5	213.5	9.4	0.9	454.2	
Terrain Deformation	38.1	30.0	14.4		82.5	
Overblowing		10.1	0.5	1.0	11.6	
Total	268.6	253.6	24.3	1.9	548.2	(27.9%)
CHEMICAL						
Loss of nutrients	52.4	63.1	19.8		135.3	
Salanization	34.8	20.4	20.3	0.8	76.3	
Pollution	4.1	17.1	0.5		21.8	
Acidification	1.7	2.7	1.3		5.7	
Total	93.0	103.3	41.9	0.8	239.1	(12.2%)
PHYSICAL						
Compaction	34.8	22.1	11.3		68.2	
Waterlogging	6.0	3.7	0.8		10.5	
Subsidence of organic soils	3.4	1.0	0.2		4.6	
Total	44.2	26.8	12.3		83.3	(4.2%)
GRAND TOTAL	749.0	910.5	295.7	9.3	1964.4§	

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†Adapted from Oldeman et al. (1990) and L.R. Oldeman (personal communication, 1991).

‡Percent of total degraded lands.

§Total land surface area of the earth is 13012.7 million hectarces.