79-296-J

Chapter 8

Soil Loss Tolerance[1]

E. L. SKIDMORE[2]

ABSTRACT

A function is developed for defining soil loss tolerance (T value) that provides for permanent preservation of the soil resource, prohibits erosion that contributes excessively to pollution, and is a function of the present soil depth. The relationship is expressed by $T(x,y,t) = (T_1 + T_2)/2 - (T_2 - T_1)/2 \cos[\pi(z - z_1)/(z_2 - z_1)]$, where $T(x,y,t)$ is tolerable soil loss rate at point (x,y), and T_1 and T_2 are lower and upper limits of allowable soil loss rate, T_1 corresponds to soil renewal rate, z_1 and z_2 are minimum allowable and optimum soil depths, and z is the present soil depth. Tolerable soil loss function between the points (T_1,z_1) and (T_2,z_2) is sinusoidal and dependent upon soil depth and $(T_2 - T_1)/2$ is the amplitude. The period is represented by the cosine argument and goes from 0 to 180 degrees for values of z between the limits of z_1 and z_2. Examples of application are given.

INTRODUCTION

The soil on which we depend for existence is a limited resource. The potential gross cropped area accessible to relatively high-yielding cultivation with present technology is about 4.2 billion ha (Revelle, 1976), of which one-third to one-half of the most productive part is already under cultivation. Arable land is limited not only in area but also in depth, quantitatively and qualitatively. Many processes can reduce the soil's current and/or potential capacity to produce desired crops. Processes that degrade soils include desertification, wind erosion, water erosion and sedi-

---

[1] Contribution from ARS-USDA, in cooperation with the Kansas Agric. Exp. Stn. Dep. of Agronomy Contribution 79-296-J.

[2] Soil scientist, ARS, USDA, Manhattan, Kansas 66506.

mentation, flooding, waterlogging, organic matter oxidation, physical deterioration, chemical pollution, salinization, alkalinization, and urbanization.

Concern that soil degradation processes be stopped or reversed has prompted comments and actions of various kinds. Lowdermilk (1951) suggested an 11th Commandment on stewardship of the land.

Food and Agriculture Organization of the United Nations (1974, 1977) recently sponsored two expert consultations for assessing soil degradation. At the first of these, the panel recommended that land be recognized as an essential and limited resource and that the adverse effect of different forms of soil degradation on future food suppliers of the world be considered. They suggested that the highest priority be given to soil conservation measures urgently needed to ensure the supply of an adequate diet for increasing populations.

At a recent board meeting[3], the Soil Science Society of America approved a resolution that land and water conservation programs be instituted that will conserve our vital soil resource, maintain its productivity, and foster a healthful environment.

A reasonable objective of soil stewardship is to maintain a soil resource that with judicious use of additional available resources of water, favorable climate, plants, and technology can produce sufficient food and fiber to meet the present and future needs of man on Earth. Obviously, accomplishing this objective depends not only on the soil resource itself but also on other resources that enhance soil productivity and the demand created by the world population. However, we will limit the following discussion to considerations of soil loss tolerance on cultivated cropland. Our objective is to develop a usable function for defining tolerable soil loss which includes the concepts developed by Stamey and Smith (1964).

They suggested that the definition of erosion tolerance must (1) provide for the permanent preservation or improvement of the soil as a resource, (2) be adaptable to the erosion and renewal rates of any soil characteristic, (3) be a function of position since at any two points on the Earth's surface the erosion and renewal rates will not necessarily be identical, (4) be applicable regardless of the cause of erosion or renewal, and (5) allow the use or depletion of any soil property (e.g., depth) in excess of present or predictable future requirements.

Conceivably, erosion of some soils such as a deep loess soil could cause more serious environmental problems than impairment of a soil resource. This suggests the need for another element in the definition of soil loss tolerance: (6) prevent erosion from contributing excessively to pollution and other environmental problems.

METHODS

Stamey and Smith (1964) developed a mathematical expression for erosion tolerance at point (x,y) of some measurable soil property.

$$I(x,y) - \int_{t_0}^{\infty}[E(x,y,t) - R(x,y,t)]\,dt \geq M(x,y) \qquad [1]$$

[3] See minutes of SSSA Board of Directors' Meeting, 7 Dec. 1978, Chicago, Ill.

Table 1. The various combinations of limits for the curves of Fig. 1.

Curve	T_1	T_2	z_1	z_2
	mm/yr†		m	
a	0.2	2.0	0.5	0.8
b	0.2	2.0	0.5	1.2
c	0.2	2.0	0.5	1.6
d	0.2	2.0	0.5	2.0
e	0.2	1.6	0.5	2.0
f	0.2	1.2	0.5	2.0
g	0.2	0.8	0.5	2.0

† When a soil has a bulk density of 1.0 g/cm³, multiply millimeters per year by 10 to convert to metric tons per hectare per year.

where I(x,y) is the position function, which gives the value of the measure of the soil property at the initial time (t_0; M(x,y) represents the minimum allowable value at (x,y) of the measure of this property; and E(x,y,t) and R(x,y,t) represent the erosion rate and renewal rate, respectively, of the measurable soil property. Equation 1 defines the concept that net change tolerance [E(x,y,t) − R(x,y,t)] integrated over time subtracted from the initial value of the measurable soil property must always exceed the minimum allowable value. However, very little progress has been made in the last 15 years to define the function of Eq. [1] so that it is of practical use.

Consider the following equation for defining tolerable degradation of some measurable soil property at point (x,y). For illustration and discussion, let us apply the equation to soil depth, although it could be used for other measurable properties, both extensive and intensive.

$$T(x,y,t) = (T_1 + T_2)/2 - (T_2 - T_1)/2 \cos[\pi(x - z_1)/(z_2 - z_1)] \quad [2]$$

Where T_1 is the lower limit of allowable rate of change of soil property at point (x,y) (here it represents soil loss per annum); T(x,y,t) equals T_1 when soil depth is at minimum allowable value so that net change function of Eq. [1] equals zero. In other words, $\int_{t_0}^{t_1}$ [E(x,y,t) − R(x,y,t)]dt equals zero and P(x,y) equals M(x,y), where P(x,y) is the present value of the soil property depth.

The upper limit of allowable soil loss rate at point (x,y) is T_2; T(x,y,t) equals T_2 when soil depth is great enough so that a further increase in soil depth would not further enhance the productive capacity of that soil at point (x,y); z is the present value P(x,y) of the soil property at point (x,y); z_1 is the minimum allowable value of the soil property at point (x,y), [M(x,y) of Eq. 1]; and z_2 is the optimum or target value O(x,y) of the soil property at point (x,y). At this point, increasing the value of z_2 would not further increase the productive capacity of that soil at point (x,y). $T_1 \leq T(x,y,t) \leq T_2$ as $M(x,y) \leq P(x,y) \leq 0(x,y)$. The relationship between the limits of T_1 and T_2 for allowable soil loss and z_1 and z_2 for soil depth is sinusoidal. The amplitude is $(T_2 - T_1)/2$.

Period is represented by $[(z - z_1)/(z_2 - z_1)]\pi$ of the cosine argument and ranges from zero to π radians or 180 degrees for values of z between the limits of z_1 and z_2. The first term of Eq. [2] is simply an amplitude offset. T(x,y,t) connects the extreme points (T_1,z_1) and (T_2,z_2) with a slope of

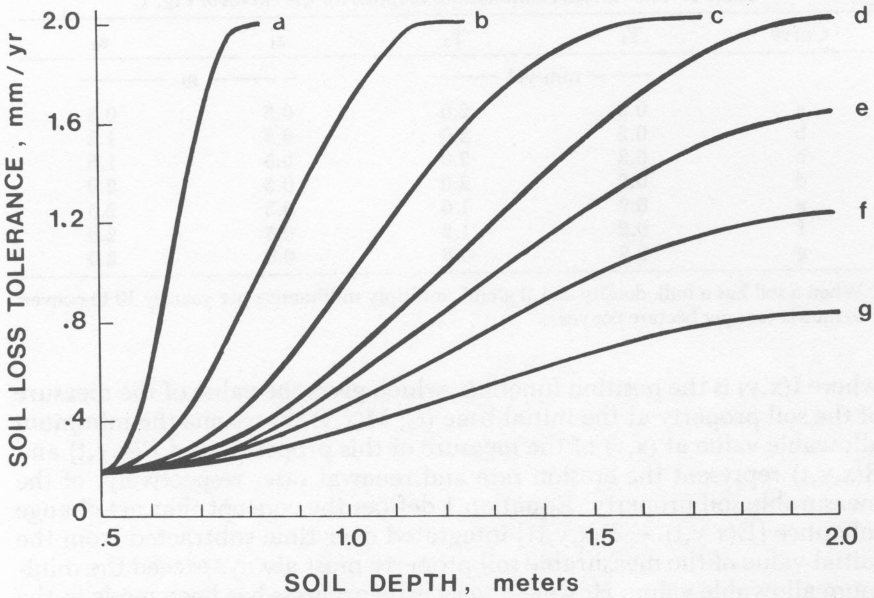

Fig. 1. Soil loss tolerance as a function of soil depth for various combinations of limits.

zero. That is, as the present value P(x,y) of the soil property depth gets closer to M(x,y), the change in T(x,y,t) with change in P(x,y) goes to zero and T(x,y,t) = R(x,y,t).

Soil loss tolerance as a function of soil depth, as defined by Eq. [2] for various combinations of limits (Table 1), is illustrated by Fig. 1. Each curve shows the values of T for the full period or half cycle of the cosine function. The lower limits were held constant. The minimum allowable soil depth M(x,y) was chosen at 0.5 m; renewal rate R(x,y,t) was chosen at 0.2 mm/year.

APPLICATION EXAMPLE

Suppose we wished to determine appropriate soil loss tolerances for a soil at (x,y) that was 1.4 m deep. We judged that the production capacity of that soil would increase with depth up to 2.0 m and that a depth of 0.5 m would be the minimum allowable. Soil renewal rate is 0.2 mm/year. We determined that maximum soil loss should never exceed 2.0 mm/year. Then, using Eq. [2], we calculated tolerable soil loss as 1.38 mm/year, or about 14 metric tons/ha•year.

When different values for present value of soil depth are substituted into Eq. [2], curve d of Fig. 1 is generated. As the soil depth approaches either limit of soil loss tolerance, the slope of the curve approaches zero.

Now we must answer the questions: How fast does the soil depth change with time if soil depth changes according to soil loss tolerance (T value), and in what manner does T value change with time? This was done by solving Eq. [3] and substituting P(x,y) for z back in Eq. [2] for n = 2,000 iterations.

$$P_i(x,y) = I(x,y) + \sum_{i=0}^{i=n-1} (R_i(x,y,t) - T_i(x,y,t)] \qquad [3]$$

where the variables are as defined previously. The results are shown in Fig. 2. Soil depth decreases rather quickly with time from the initial value of 1.4 m, then levels off with time as the T value approaches the soil renewal rate (0.2 mm/year).

Now, for another example, suppose that a very deep soil of uniform depth had 0.5 m soil that could be removed without affecting its current or future productivity. Furthermore, we assumed that z_1 and z_2 are 1.0 and 1.5 m, respectively; and T_1 and T_2 are 0.1 and 2.0 mm/year, respectively. In this case, Eq. [2] and [3] yield the results shown in Fig. 3. Soil loss tolerance remains constant at the maximum value until soil depth equals 1.5 m, then decreases as soil depth decreases below 1.5 m.

DISCUSSION

In these applications, reasonable values for the upper and lower limits of T value and soil depth were assumed. The key to the successful use of Eq. [2] in describing soil loss tolerance lies in the rationale and procedure for determining limit values. Some may argue that we do not need the upper limit of T value because only the lower limit is important in permanently preserving the soil resource. However, knowing the upper limit is important for meeting criterion No. 6. Clean Air Amendments (1970) and Federal Water Pollution Control Act Amendments (1972) will not allow us to permit wind and water erosion to occur without consideration of the environment. Also, we should guard against soil loss where the damage costs to the environment are greater than the costs of preventing the loss.

Figures 2 and 3 indicate that soil depths change rather slowly with time for the conditions of these examples. In these cases, the renewal function was constant. We need more information on renewal rates for specific locations and conditions and how renewal rates can be accelerated. Renewal rates from weathering of the basalt underlying shallow loess soils in the Pacific Northwest is slow as compared with those of shale parent material of some soils in the Southeast. We should not permit soil loss to proceed to the extent that it lowers the producing capacity of the soil, either immediately or in the long-term, more than it would cost to prevent the loss.

The minimum allowable soil depth could be defined in terms of the present soil depth and/or, according to the judgment of local soil scientists, the depth of soil required to preserve high-level crop production. Results now being obtained on reclaiming drastically disturbed lands should give additional insights into depth and quality of soil needed for particular production levels.

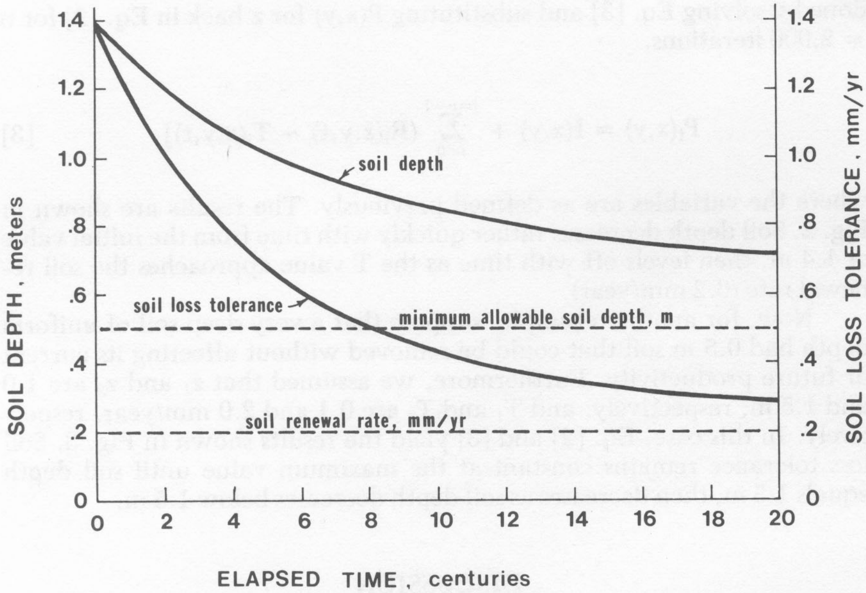

Fig. 2. Change in soil depth and T value as soil loss proceeds at the tolerable rate.

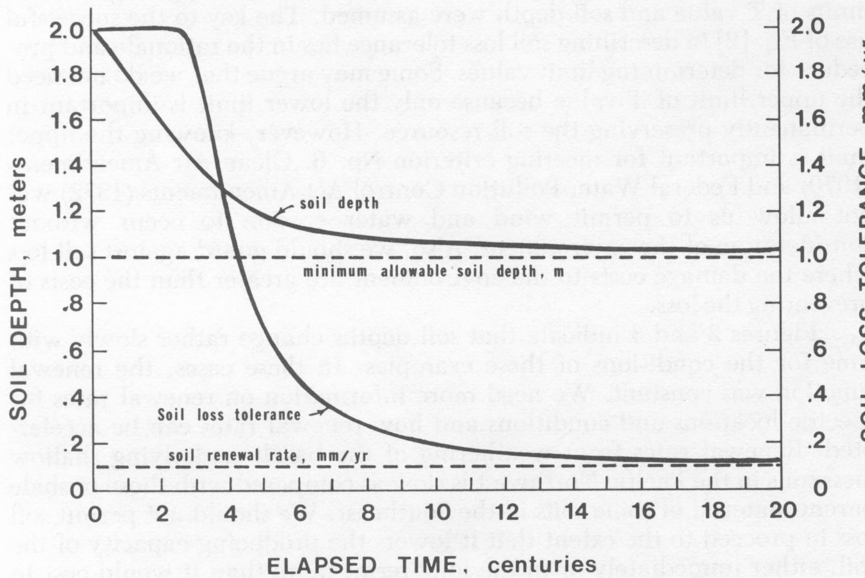

Fig. 3. Change in soil depth and T value as soil loss proceeds at the tolerable rate.

The optimum soil depth could also be defined in terms of the present soil depth or according to the judgment of soil scientists who know local conditions and limiting resources. In addition to meeting T values, we should increase the quantity and quality of the soil resource wherever the cost of doing so is lower than the value of the increased production capacity.

So far we have discussed the soil property depth as if it were measurable, which it is. However, we must establish some guiding criteria for that measurement. Do we measure A + B horizons, rooting depth of commonly grown crops, depth to impervious layer, or something else, and do we establish a weighting factor for quality of soil material giving more credit to the more desirable topsoil? These questions and those pertaining to defining limits can be answered best by consensus of concerned and knowledgeable scientists representing various groups like the Soil Conservation Service, Agricultural Research, and Cooperative State Research Service.

With appropriate limits, Eq. [2] would satisfy criteria for defining erosion tolerance mentioned earlier and be very useful for determining T value. Then, using the WEQ (Woodruff and Siddoway, 1965; Skidmore and Woodruff, 1968) and the USLE (Wischmeier and Smith, 1978), we can implement erosion control practices to maintain a soil resource that can produce food and fiber to meet our present and future needs.

LITERATURE CITED

Clean Air Amendments of 1970. 1970. Public Law 91-604. U.S. Code Congressional and Administration News. 1954–2001.

Federal Water Pollution Control Act Amendments of 1972. 1972 Public Law 92-500. U.S. Statutes at Large 86:816–903.

Food and Agriculture Organization of the United Nations. 1974. A world assessment of soil degradation—an international programme of soil conservation. Report of an expert consultation on soil degradation, Rome. 40 p.

————. 1977. Assessing soil degradation—report of an FAO/UNEP expert consultation, Rome, FAO Soils Bull. 34. 83 p.

Lowdermilk, W. C. 1951. Conquest of the land through seven thousand years. USDA, SCS, MP-32. 38 p.

Revelle, Roger. 1976. The resources available for agriculture. Sci. Am. 235:164–178.

Skidmore, E. L., and N. P. Woodruff. 1968. Wind erosion forces in the United States and their use in predicting soil loss. USDA, ARS, Agric. Handb. No. 346. 42 p.

Stamey, W. L., and R. M. Smith. 1964. A conservation definition of erosion tolerance. Soil Sci. 97:183–186.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses—a guide to conservation planning. USDA, Agric. Handb. No. 537. 58 p.

Woodruff, N. P., and F. H. Siddoway. 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29:602–608.