

The Evolution of Soil Loss Tolerance and Its Importance to Soil Productivity Protection, including Ecosystem Services

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Abstract

Soil erosion research provided the concept of soil-loss tolerance, which is a value of soil loss that, if exceeded, reduces crop productivity and soil fertility. Much of the modern history of soil science involved research to provide quantitative estimates of the equilibrium involving soil loss and soil formation. With the advent of soil health indicators and their laboratory protocols, new soil knowledge and visions provided additional assessment technologies for producers to maintain or improve their soil's vitality. However, there exists a need for the establishment of field evaluation guidelines to reveal the landowners' success in augmenting key soil health indicators. Adopting soil erosion concepts involving the balance of soil loss and soil formation rates and substituting actual and desired soil indicator values will gauge the current soil health status. The application for evaluating ecosystem services is an important land management objective.

Keywords

Erosion, Soil Health, Soil Quality, Productivity Index, Ecosystem Services

1. Introduction to Erosion and Tolerance

Erosion is defined as the detachment, movement, and deposition of soil, sediment, or rock by water, wind, ice, or gravity (American Society of Agronomy, Crop Science Society of America, & Soil Science Society of America, 2008; Morgan, 2005). Amundson et al. (2015) discussed how human activities, such as soil erosion, are rapidly degrading soil and its potential impact on the human condition. For a given soil, elevated erosion rates attributed to human activity are termed accelerated erosion. In 1941, Hays proposed the term soil-loss tolerance, that is, a soil-loss limit for

a particular soil to maintain soil productivity (Hays & Clark, 1941). Wischmeier and Smith (1978) defined the “soil-loss tolerance as the maximum level of soil erosion that will permit a high level of crop productivity to be maintained indefinitely.” The first soil-loss tolerances were based on soil depth (Stamey & Smith, 1964). Subsequently, soil-loss tolerances were based on crop productivity, then termed productive soil potential. In India, Bhattacharyya et al. (2011) stated that the soil-loss tolerance is “the maximum amount of soil which can be removed annually before the long-term soil productivity is adversely affected.” They inferred that the soil-loss tolerances ranged from 2.5 to 12.5 Mg ha⁻¹ yr⁻¹ compared to the regional default value of 11.2 Mg ha⁻¹ yr⁻¹.

Hall et al. (1985) specified key criteria for quantitatively specifying soil-loss tolerance. The foremost influences include: 1) soil formation rates vs. soil loss rates, 2) long-term crop or forest productivity, 3) soil properties (soil depth, texture, structure, organic matter content, and drainage, permeability), and 4) site-specific conditions (previous erosion, climate, topography, and vegetation). One major issue involves quantitatively estimating individual soil-forming rates. Li et al. (2009) reviewed the development of soil-loss tolerance values and listed influencing factors established by the United States Department of Agriculture. The soil-loss tolerance factors included 1) the rate of soil formation from parent material, 2) the rate of topsoil formation from subsoil, 3) reduction of crop yield by erosion, 4) soil depth, 5) changes in soil properties favorable for plant growth, 6) loss of plant nutrients, 7) likelihood of rill and gully formation, and 8) sediment deposition. The authors proposed that tolerance for agrochemicals and the self-restoration capacity of ecological environments should be included. Alexander (1988b) argued that 1) soil organic matter maintenance and 2) protecting soil depth are important attributes for assessing soil-loss tolerance. Duan et al. (2012) proposed that key factors influencing soil loss tolerance include 1) soil type and other soil properties, 2) topography, 3) erosion and the soil’s current situation, 4) high erosion rates, and 5) excessive cultivation.

In the European portion of Russia, Kuznetsov and Abdulkhanova (2013) calculated soil-loss tolerances for chernozems (black earth soils developed in grasslands) using a modified Skidmore equation (Skidmore, 1982). The soil loss tolerance values were obtained with consideration of soil type, soil erodibility, and crop rotation patterns. The maximum possible value of 10 t ha⁻¹ yr⁻¹ was obtained for noneroded chernozem soils regardless of the crop rotation, whereas soil-loss tolerances for noneroded podzolized chernozems were somewhat lower, and these soil-loss tolerances were influenced by the crop rotation.

If the rate of soil loss exceeds the soil formation rate, then the soil must be evaluated to provide a suitable soil loss rate to sustain the soil as a plant growth medium (Hall et al., 1985). Alexander (1988a) noted that the rates of soil formation influence tolerable soil losses, especially in shallow soils. Employing geochemical data from 18 noncarbonate lithology watersheds, Alexander estimated the rates of soil formation ranged from 0.02 to 1.9 Mg ha⁻¹ yr⁻¹. The rates were dependent on

the water run-off, and the ratio is the soil mass divided by the mass of bedrock weathered to produce that soil mass.

Recently, [Carollo et al. \(2023\)](#) proposed defining “tolerable soil loss” as influenced by 1) a plant cover and management factors, and 2) equating tolerable and annual soil losses for a given return period. They inferred that the tolerable soil loss is related to the soil’s erodibility. [Stefano and Vito \(2016\)](#) proposed that soil-loss tolerance values differ based on variations in the inherent soil erodibility and soil formation rates, often assessed through productivity indices and soil organic matter contents within the soil profile. They also inferred that the soil-loss tolerance should consider soil productivity as well as downstream water pollution and reservoir sedimentation.

[Chandel and Hadda \(2017\)](#) stressed that productivity is of utmost concern in evaluating soil-loss tolerance; however, soil profile thickness, rate of soil formation, and productivity index should be evaluated in the assessment of soil-loss tolerance. [Duan et al. \(2015\)](#) stressed that sustainable land management must consider soil conservation, organic matter content, and nutrient accumulation when addressing erosion resulting from land conversion. In Sichuan, China, [Liu et al. \(2009\)](#) showed that Entisol formation rates varied because 1) soil type and parent material/bedrock, 2) vegetation types, and 3) soil depth. Soil formation rates ranged from 800 to 1200 Mg km⁻² yr⁻¹. [Schertz and Mark \(2006\)](#) reasoned that soil-loss tolerance values need to consider the protection of natural resources.

The purpose of this study was to: 1) review the development of the soil-loss tolerance and its criteria, and 2) explore future developments and applications to guarantee soil ecosystem protection.

2. Early Development Involving Tolerance Estimations and Their Implementation

[Stamey and Smith \(1964\)](#) provided a mathematical expression for erosion soil-loss tolerance for an x, y coordinate:

$$I(x, y) = \int [E(x, y, t) - R(x, y, t)] dt \geq M(x, y)$$

where $I(x, y)$ is the position function (provides value of the soil property being considered), $E(x, y, t)$ is the erosion rate, $R(x, y, t)$ is the pedogenic soil renewal (formation) rate, $M(x, y)$ is the minimum allowable value, and t is time. The integration is carried out from $t = 0$ to t . The above equation requires estimates of the erosion rate, the renewal rate (the rate at which the soil replenishes the degradation attributed by erosion), and the minimum allowable value (the soil property status that must not be exceeded to support soil sustainability). For clarification, when the erosion or renewal rates are provided in units of mm yr⁻¹, then if the bulk density is 1.0 g cm⁻³, multiplication by 10 converts these units to metric tons ha⁻¹yr⁻¹.

The pedogenic soil renewal rate is a difficult value to determine, given that soil properties develop at distinctively different time scales. Parent materials weather at distinctive rates ([Buol et al., 2003](#)). For example, soil organic matter establish-

ment may only require several hundred years to develop, whereas multiple millennia may be required to develop an argillic horizon.

Skidmore (1982) provided a mathematical expression that estimates the soil property value as a function of x , y , and t .

$$T(x, y, t) = (T_1 - T_2)/2 - ((T_2 - T_1)/2) \cos [\pi(X - Z_1)/(Z_2 - Z_1)]$$

where $T(x, y, t)$ is the soil property value, T_1 is the lower limit of the allowable soil property rate of change, and T_2 is the upper limit of the allowable soil property rate of change. Frequently, T_1 and T_2 are soil loss rates (mm yr^{-1}), and T_1 is less than T_2 , Z_1 is the minimum allowable value of the soil property under consideration, whereas Z_2 is the optimum value of the soil property under consideration. X is the actual value of the soil property. Skidmore's manuscript provides examples where the predicted soil loss tolerance is predicted using the minimum allowable soil depth, the soil renewal rate, and the actual soil depth.

3. Evolution of Soil Erosion Modeling

Laflen and Flanagan (2013) reviewed the technical details and history of the Universal Soil Loss Equation (USLE). With the advent of additional criteria, the revised Universal Soil Loss Equation (RUSLE) improved soil erosion predictability. For example, the RUSLE soil erodibility considers gravel content to reduce the soil erodibility. Akpa et al. (2024) discussed the evolution of the RUSLE and its application for tropical soils. The success of the USLE and RUSLE in estimating raindrop-induced soil loss for production fields resulted in the development of the Water Erosion Prediction Project (WEPP) model. The WEPP Erosion Prediction Project Model predicts the likelihood of erosion for field-sized land parcels, and considers climate, hydrology, soil water dynamics, erosion types, field management and tillage, residue management, plant growth, and surface impoundments (Flanagan et al., 2007). The WEPP model provides estimations of rill erosion and other features; however, the model requires a greater degree of data collection.

Ecosystem services are natural processes that are critical to providing community health and regional economic prosperity. Four frequently stated ecosystem service categories are (with specific ecosystem services): 1) provisioning (food, water, timber), 2) regulating (climate control, pollination, flood protection), 3) supporting (nutrient cycles, habitat), and 4) cultural (recreation, spiritual, aesthetic) (Aide and Braden, 2023; Aide et al., 2023). Renschler and Harbor (2002) forwarded the idea that offset damage should be reflected in the soil-loss tolerance. In a review, Stavi et al. (2016) developed a conceptual model where soil functions and ecosystem services were compared across conventional, conservation, and integrated agricultural systems. Ecosystem services and soil functions were most protected in conservation systems, whereas crop yields were enhanced for integrated systems.

With increased global environmental and climate stresses, Liu et al. (2015) forecast that soil-loss tolerance studies are becoming more important to ecological and environmental investigations. The authors argue that ecosystem sustainability constantly involves complex interactions between biotic and abiotic/envir-

mental systems. However, turning this information into actionable plans is not fully operational.

4. Tolerance Usage Evolving to Incorporate Our Emerging Understanding of Ecosystem Services and Soil Health

Soil health is evaluating the soil's capacity to function as a living ecosystem, supporting plants, animals, and humans by regulating water, nutrient cycling, and sustaining biodiversity. Some researchers include filtering and alleviating potential pollutants (Aide et al., 2023; Timilsina et al., 2025; Rinot et al., 2019). Rinot et al. (2019) stated that soil health maintenance is a prerequisite for properly functioning ecosystem services. Rinot et al. (2019) further proposed that soil ecosystem services must have scoring systems for assessing the selected individual services within the provisioning, regulating, and supporting categories. In India, Timilsina et al. (2025) provided context for the interplay between soil health, agricultural sustainability, and policy innovation.

Soil health indicators are frequently used to estimate the soil's health status. Liptzin et al. (2022) evaluated soil health carbon indicators and noted that the 24-hr potential carbon mineralization and the soil organic carbon content were strongly influential for assessing the soil's health status. Investigating Wisconsin soils, Bandura et al. (2026) evaluated and supported soil organic matter, soil organic carbon, potentially mineralizable carbon, permanganate oxidizable carbon, total nitrogen, potentially mineralizable nitrogen, autoclaved citrate extractable protein, and aggregate stability as important soil health indicators. Bagnall et al. (2023) noted that organic carbon, carbon mineralization, and aggregate stability were sensitive indicators for assessing tillage, cover crops, crop rotations, residue, and nutrient amendments. **Table 1** is a listing of widely employed soil health indicators and their evaluation potential.

The National Commodity Crop Productivity Index (NCCPI) is a measure of a soil's productivity for non-irrigated commodity crops within a specific geographical zone (Albers et al., 2022). The NCCPI provides ratings of 0 to 1, with 1 being the most productive. Key input data includes 1) soil properties: (soil organic matter content, soil texture, cation exchange capacity, pH, and available water capacity), 2) landscape features (slope, erosion potential, and flooding, and other hazards), 3) climatic data (frost-free days, annual precipitation). The model focuses on non-irrigated commodity crops like corn, soybeans, and wheat. Duan et al. (2017) noted that soil productivity indexes are important databases to better estimate soil-loss tolerance. One major limitation of the NCCPI is that it does not reflect land management.

In China, with established alfalfa-corn rotation (*Medicago sativa* and *Zea mays*), Chen et al. (2019) noted that soil organic carbon was increased 30% under reduced-tillage compared to conventional tillage. Compiling a global data analysis, West and Post (2002) similarly documented that reduced tillage across many rotations, compared to conventional tillage, may typically sequester $57 \pm 14 \text{ g C m}^{-2}$

yr⁻¹, with approaches to carbon sequestration maximum for this land management in 5 to 10 years.

Table 1. Soil health indicators and their information provision.

Indicator	Information about Soil Health
Soil Organic Matter (SOM)	Total amount of organic material, including carbohydrates, proteins, bacteria, and fungi, residue, roots, and other organisms.
Soil Organic Carbon (SOC)	Total amount of organic material, based on a carbon basis. (approximately 50% of soil organic matter).
Potentially Mineralizable Carbon	Converted SOC to CO ₂ by soil microbial communities under specific time, temperature, and moisture conditions.
Permanganate Oxidizable Carbon	The fraction of SOC that is likely related to biological decomposition.
Total Nitrogen	All forms of soil nitrogen, including organic and inorganic nitrogen.
Potentially Mineralizable Nitrogen	Portion of soil organic nitrogen converted to plant available forms (inorganic nitrogen).
Autoclaved Citrate Extractable (ACE) Protein	Concentration of protein-like substances in SOM (primary mineralizable nitrogen—available to soil microbial communities).
Aggregate Stability	The ability of soil aggregates to resist disintegration because of tillage and water/wind erosion.
Available Water Capacity	The maximum amount of plant available water.
Soil Electrical Conductivity	Estimates the influence of soil electrolytes.
Soil Enzymes	Sources of enzymes include living and dead microbes, plant roots, and other biota.
Soil Respiration	Measure of biological activity and decomposition.
Soil pH	Intensity of acidity or alkalinity.

5. A Proposal for Utilizing Soil Health Indicators to Re-Image Soil-Loss Tolerances to Reflect Ecosystem Service Assessment

Skidmore (1982) provided a quantitative estimation for estimating soil-loss tolerance. As proposed by Skidmore, the soil-loss tolerance equation selects a soil property regarded as essential for maintaining agricultural productivity. Early investigations primarily regarded soil depth; however, other properties were also proposed. One difficulty was that multiple soil properties may need to be field evaluated to provide a more realistic soil-loss tolerance estimation; thus, a qualitative and holistic evaluation of soil-loss tolerance values is provided by experienced soil scientists.

The NCCPI has been utilized to better reflect sustainability. In the Red River basin in China, Duan et al. (2017) proposed that farmland tolerance values should not reflect soil formation rate and offset damage, and that sustainable land management is of paramount importance. Duan et al. (2017) further proposed that regional tolerance values should be partitioned by soils and their functions: 1) farmland by soil productivity, 2) forest and grasslands by their ecological services, 3) mineral and industrial areas by material supply, and 4) natural reserves by their environmental

protection.

With the advent of soil health as an important soil standpoint, the possibility of modifying soil-loss tolerance to assess specific soil health outcomes is an emerging research initiative. Selecting soil health indicators, such as those listed in **Table 1**, may be evaluated with modified equations employing Skidmore's original intent. Then experienced soil scientists, backed with emerging digital technologies, will be able to provide soil-loss tolerance values to protect ecosystem services. With such soil-loss tolerance estimates, producer acceptance may be more realized with data assurances.

Consider the scenario where we have a soil organic carbon renewal rate of $20 \text{ g C m}^{-2} \text{ yr}^{-1}$, and we estimate that the maximum permissible carbon loss rate is $40 \text{ g C m}^{-2} \text{ yr}^{-1}$. Let us suppose that the minimum soil organic carbon content is 0.5% and the optimum soil organic carbon content is 1.0%. Modifying the Skidmore (1982) equation, we obtain **Figure 1**. Thus, specifying soil organic carbon content, we may then ascertain the permissible carbon loss rate. Other soil health indicators may be similarly formulated.

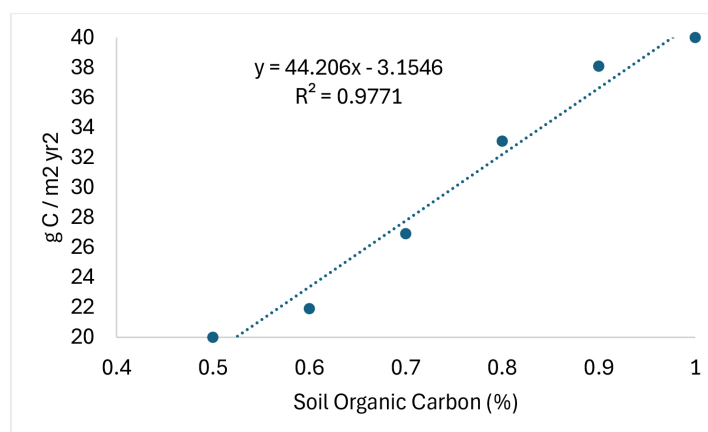


Figure 1. Relationship between the change in annual soil organic carbon per land area ($\text{g C m}^{-2} \text{ yr}^{-1}$) and the soil organic carbon content (%).

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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