DEFINITION OF TOLERABLE SOIL EROSION VALUES[1]

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SUMMARY

Although the criteria for defining erosion tolerance are well established, the limits generally used are not consistent with natural, economical and technological conditions. Rates greater than soil formation can be accepted only until a minimum of soil depth is reached, provided that they are not associated with environmental hazard or productivity losses. A sequence of equations is presented to calculate erosion tolerance rates through time. The selection of equation parameters permits the definition of erosion tolerance rates in agreement with environmental, social and technical needs. The soil depth change that is related to irreversible soil degradation can be calculated. The definition of soil erosion tolerance according to these equations can be used as a guideline for sustainable land use planning and is compatible with expert systems.

Index terms: Erosion tolerance, soil depth change, land use planning.

RESUMO: *DEFINIÇÃO DE VALORES TOLERÁVEIS DE EROSÃO*

Apesar dos critérios utilizados para a definição de valores toleráveis de erosão estarem bem definidos, os limites geralmente utilizados não são consistentes com as condições naturais, econômicas ou tecnológicas. Valores superiores à taxa de renovação do solo podem ser aceitos apenas até ser alcançada uma profundidade mínima do solo, associado ao fato de não poder ser aceita a degradação ambiental ou a perda de produtividade das culturas. É apresentada uma seqüência de equações para o cálculo da erosão tolerável ao longo do tempo. A seleção dos parâmetros das equações permite a definição da tolerância de perda de solo em concordância com os condicionantes ambientais, sociais e técnicos. A alteração da profundidade do solo que se relaciona com a sua degradação irreversível pode ser calculada. A definição da tolerância de perda de solo por estas equações pode servir de subsídio para o planejamento racional e sustentável do uso das terras e é compatível com sistemas automatizados.

Termos de indexação: tolerância de perda de solo, alteração de profundidade do solo, planejamento do uso da terra.

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INTRODUCTION

Soil is an essential natural resource, available in limited quantities. Under natural conditions, material is removed from the soil surface mainly by the action of water and/or wind in a process called erosion, the main natural soil depth reducing factor. If the soil material is deposited lower, on the foot of a hill or mountain, concave slope, flood plain or other trapping position, without the interference of streams or rivers, it is called colluvium. If it is taken away by a river and deposited further on a flood plain, it is called alluvium. Colluvium and alluvium both are forms of sedimentation, a soil depth increasing factor. At the lower boundary of the soil, rocks are weathered and incorporated into the soil. This is part of the process called soil formation and also a soil depth increasing factor. If the erosion rate equals the soil depth increase rate, caused by the sum of soil depth increasing factors, soil depth does not vary with time. In cases where the erosion rate is smaller than the soil depth increase rate, soils become deeper with time. This is the case for most well drained densely vegetated soils, especially those from tropical regions. However, agriculture can substantially modify soil formation and erosion/sedimentation rates. With the removal of the natural soil cover and its replacement by crops, the soil's protection against the action of rain and wind will be absent or less efficient. As a consequence, the erosion rate increases and may become greater than the soil depth increase rate, resulting in soil depth loss.

The use and management of soils must consider how to preserve it from excessive depth loss and consequent degradation of its physical, chemical and biological properties. However, information on how to determine the erosion tolerance is limited. An important step forward on the issue was made when Stamey & Smith (1964) suggested a conceptual model emphasizing several points to be considered for determining erosion tolerance: "It should: 1) provide for the permanent preservation or improvement of soil as a resource, 2) be adaptable to the erosion and renewal rates of any soil characteristics, 3) be a function of position, 4) be applicable regardless of the cause of erosion or renewal and 5) be based on the assumption that if any soil property is available in excess of present or predictable future requirements, it is tolerable to use the excess". They developed a general mathematical equation for erosion tolerance considering these points. Later, Skidmore (1982) added that erosion tolerance should weigh erosion from the standpoint of pollution and other environmental concerns and developed an equation for erosion tolerance as a function of the actual soil depth.

Considering that some of the above criteria, like available excess and environmental concern, are time dependent, fixed values for soil erosion tolerance (Grossman & Berdanier, 1982) can only be valid for limited time. This is confirmed by the fact that those values are almost always greater than the estimated soil formation rates (McCormack et al., 1982).

The objective of this paper was to present equations for determining tolerable erosion rates according to the conditions stated by Stamey & Smith (1964) and Skidmore (1982) and show some examples of its applicability.

METHODS

In order to establish the relationship between time and tolerable erosion rates some parameters were defined. The change of actual erosion rate (E_0, mm y^{-1}) to a new erosion rate E_1 (mm y^{-1}) can be mathematically described as follows:

$$E_t = E_0 + (E_1 - E_0)\left(\frac{t - t_0}{t_1 - t_0}\right)^m ; t_0 \le t \le t_1; m > 0 \qquad (1)$$

where E_t (mm y^{-1}) is the erosion rate at time t (y), t_0 (y) is the actual time, t_1 (y) is the time when E_1 is reached and m is an exponential factor allowing the modification of the shape of the E_t curve. Usually, the actual erosion rate E_0 is found to be too high and will have to be reduced to a more acceptable E_1 erosion rate. At t_1, new conditioning factors might be determined and consequently it might be decided that erosion rate E_2 is to be reached at some future time t_2. In this way, n different intervals may be defined. Indexing i ($1 \le i \le n$), according to equation (1):

$$E_t = E_{i-1} + (E_i - E_{i-1})\left(\frac{t - t_{i-1}}{t_i - t_{i-1}}\right)^{m_i} ; t_{i-1} \le t \le t_i; m_i > 0 \qquad (2)$$

Soil depth change (Δz, mm) will occur according to the difference between soil depth increase rates (P, mm y^{-1}) and erosion rates integrated along time:

$$\Delta z = p - e \qquad (3)$$

where:

$$p = \int_{t_0}^{t} P\,dt = \int_{t_0}^{t} F\,dt + \int_{t_0}^{t} S\,dt \qquad (4)$$

with F being the soil formation rate due to rock weathering (mm y^{-1}) and S being the sedimentation rate (mm y^{-1}), and

$$e = \int_{t_0}^{t} E\,dt \qquad (5)$$

Considering E to be described by equation (2), it follows that:

$$e = \sum_{i=1}^{n-1}\left\{E_{i-1}(t_i - t_{i-1}) + \frac{(E_i - E_{i-1})(t_i - t_{i-1})}{m_i + 1}\right\} +$$

$$+ E_{n-1}(t - t_{n-1}) + \frac{(E_n - E_{n-1})(t_n - t_{n-1})}{m_n + 1}\left(\frac{t - t_{n-1}}{t_n - t_{n-1}}\right)^{m_n + 1} \qquad (6)$$

where n is the number of periods of time t. Similar equations can be deduced for f and s:

$$f = \sum_{i=1}^{k-1}\left\{F_{i-1}(T_i - T_{i-1}) + \frac{(F_i - F_{i-1})(T_i - T_{i-1})}{M_i + 1}\right\} + F_{k-1}(t - T_{k-1}) + \frac{(F_k - F_{k-1})(T_k - T_{k-1})}{M_k + 1}\left(\frac{t - T_{k-1}}{T_k - T_{k-1}}\right)^{M_k+1} \quad (7)$$

$$s = \sum_{i=1}^{r-1}\left\{S_{i-1}(\tau_i - \tau_{i-1}) + \frac{(S_i - S_{i-1})(\tau_i - \tau_{i-1})}{\mu_i + 1}\right\} + S_{r-1}(t - \tau_{r-1}) + \frac{(S_r - S_{r-1})(\tau_r - \tau_{r-1})}{\mu_r + 1}\left(\frac{t - \tau_{r-1}}{\tau_r - \tau_{r-1}}\right)^{\mu_r+1} \quad (8)$$

where k and r are the number of periods of time T and τ for f and s respectively, and M and μ are exponential factors allowing the modification of the shape of the curves and $T_0 = t_0 = \tau_0 = 0$ and $t_{n-1} < t \leq t_n$, $T_{k-1} < t \leq T_k$ and $t_{r-1} < t \leq \tau_r$.

DISCUSSION

Soil formation due to rock weathering is affected by changes in rainfall amount, average temperatures, water infiltration rate, type of soil cover and other environmental or anthropic factors. The available data on soil formation rates are disperse and rare and the low rate of the process combined with the difficulty of its measurement at the soil-rock border makes the precise establishment not possible. Owens & Watson (1979) found soil formation rates ranging from 0.004 mm y^{-1} up to 0.011 mm y^{-1} in Rhodesia. Wakastsuki & Rasyidin (1992) found values ranging from 2,700 to 5,700 kg ha^{-1} y^{-1} in southwestern Japan. Miklos (1992) studying the formation of Alfisols and Oxisols due to biological activity in Brazil, obtained soil formation rates of approximately 0.5 mm y^{-1}. Friend (1992), reviewing the literature on this subject found soil formation rates varying from 0.01 mm y^{-1} to 8.5 mm y^{-1}, and considered values between 0.12 mm y^{-1} and 0.25 mm y^{-1} as normal. Soil depth increase as a consequence of sedimentation can be estimated considering the relative site position in the landscape.

However, to show some examples of the applicability of the equations soil depth increase rate, i.e. soil formation rate plus sedimentation rate, was assumed to be constant. Then, the substitution of equations (4) and (6) in (3) yields:

$$\Delta z = P(t - t_0) - \left[\sum_{i=1}^{n-1}\left\{E_{i-1}(t_i - t_{i-1}) + \frac{(E_i - E_{i-1})(t_i - t_{i-1})}{m_i + 1}\right\} + E_{n-1}(t - t_{n-1}) + \frac{(E_n - E_{n-1})(t_n - t_{n-1})}{m_n + 1}\left(\frac{t - t_{n-1}}{t_n - t_{n-1}}\right)^{m_n+1}\right] \quad (9)$$

When defining the duration of a period in which erosion levels will have to change the degree of emergency of interference should be taken into account. If a water reservoir is being settled fast, a rapid interference may be needed to prevent water supply problems. In the case that no serious environmental problems or immediate productivity losses are expected, but erosion rates are too high to maintain sustainable agriculture in a more distant future due to excessive soil depth loss, the time span to reduce erosion can and should be longer, avoiding technology non adoption problems (Fujisaka, 1994). Land tenure, markets, equipment and technological procedures may take several years to be changed, even if all other conditions and the consent from the farmers are provided for. The definition of the number of time intervals can be made previously or after the occurrence of a substantial change in the erosion tolerance conditioning criteria. The first period of time should always begin at present time with the actual erosion rate.

The erosion rate to be reached at the end of time period i (target erosion rate, E_i) can be established by ecological, economic, social or political criteria. Long term soil productivity maintenance (Pierce et al., 1984), control of sedimentation hazard in water reservoirs (Lo, 1994), impact of erosion associated contaminants (Clark II et al., 1985), effect of erosion control on farmers income (Timmons & Amos, 1982) or soil formation (Alexander, 1988) may be used as parameters for E_i definition.

For example, in high input tropical agricultural systems on deep and uniform Oxisols the best criteria for defining target erosion rate at short and medium periods of time may be environmental factors since depth loss is not an immediate problem. In moderately deep or shallow soils where any depth reduction is a loss of space for root development, soil depth increase rate may be the best target erosion rate. In developing regions, where food supply may be a critical social problem, the impact of erosion control costs on farmer's incomes, and consequently their economical survival, may fix short term target erosion rates. Considering a medium time period the environmental hazard associated to soil erosion may define the tolerable rate and in a more distant future the sustainable maintenance of the productivity. In an even more distant future soil depth increase rates will have to be the target for erosion rates, in order to maintain soil depth.

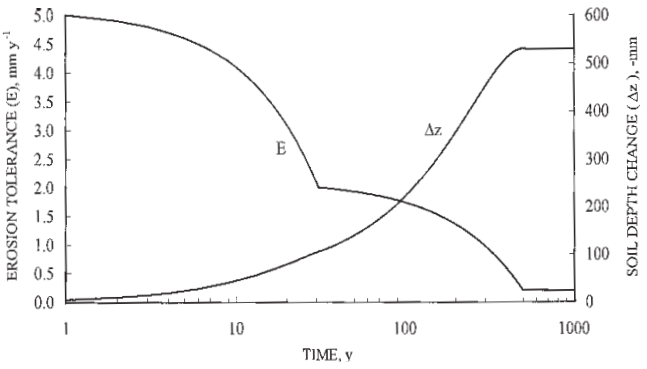

Figure 1. Shows an example of erosion tolerance determination considering the following values: E_0 = 5.0 mm y^{-1}, P = 0.2 mm y^{-1}, t_1 = 30 y, E_1 = 2.0 mm y^{-1}, t_2 = 500 y, E_2 = 0.2 mm y^{-1} and $m_1 = m_2 = m_3 = 1.00$.

The applicability of the proposed model depends on the accuracy with which the equation parameters can be determined or estimated. Erosion rates usually cannot be measured but can be estimated by the Universal Soil Loss Equation USLE (Wischmeier & Smith, 1978) or more recent models like the Water Erosion Prediction Project WEPP (Lane & Nearing, 1989). These models can also be used to identify which practices will be needed to reduce soil erosion and allow economical evaluations on its applicability.

The soil depth change (Δz, mm) at the end of a 500 y period would be of -524.4 mm. In this example the considered actual erosion E_0 of 5.0 mm y^{-1} had to be reduced rapidly due to environmental hazard or productivity losses. A period of 30 y was chosen to achieve the E_1 = 2.0 mm y^{-1} in order to perform the required production and economical adjustments. Within this first 30 y period the soil depth change was -103.3 mm, i.e. 20% of the total expected soil depth change after 500 y. The E_1 = 2.0 mm y^{-1} was considered the erosion tolerance value at which no serious environmental or productivity loss problems are expected, but since this value is higher than the considered soil depth increase rate, the soil will become shallower. Therefore, this value can be tolerated only until a minimum soil depth is reached. In this example it was assumed that after 500 y the soil will have reached its minimum depth without restrictions for root development. From then on, soil erosion rates should not exceed soil depth increase rates in order to avoid more soil depth loss.

The soil depth change at the end of the 500 y period would be of -216.9 mm. In this example, the same actual conditions as in figure 1 were assumed, but the total soil depth change at time t_3 should be reduced. This may be due to a shallower soil, in which the minimum soil depth would be reached faster, or to different criteria resulting in an other estimation of minimum soil depth. The adoption of a second target erosion tolerance rate of E_2 = 0.5 mm y^{-1} at time t_2 = 80 y reduced the final soil depth change from -524.4 mm (Figure 1) to -216.9 mm without changing the erosion rates from t_0 until t_1 = 30 y.

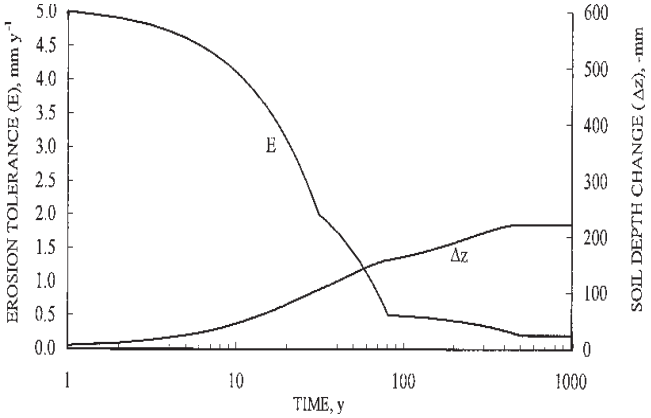

Figure 2 shows an example of erosion loss tolerance determination considering the following values: E_0 = 5.0 mm y^{-1}, P = 0.2 mm y^{-1}, t_1 = 30 y, E_1 = 2.0 mm y^{-1}, t_2 = 80 y, E_2 = 0.5 mm y^{-1}, t_3 = 500 y, E_3 = 0.2 mm y^{-1} and $m_1 = m_2 = m_3 = m_4$ = 1.00.

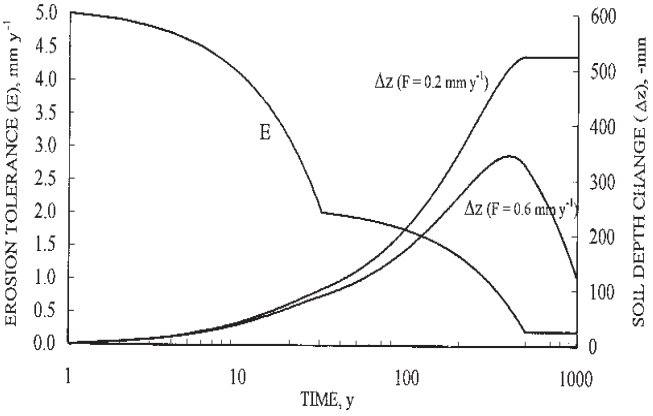

Figure 3 shows an example of erosion tolerance determination considering the following values: E_0 = 5.0 mm y^{-1}, t_1 = 30 y, E_1 = 2.0 mm y^{-1}, t_2 = 500 y, E_2 = 0.2 mm y^{-1}, $m_1 = m_2 = m_3$ = 1.00 and two soil depth increase values, P = 0.2 mm y^{-1} and P = 0.6 mm y^{-1}.

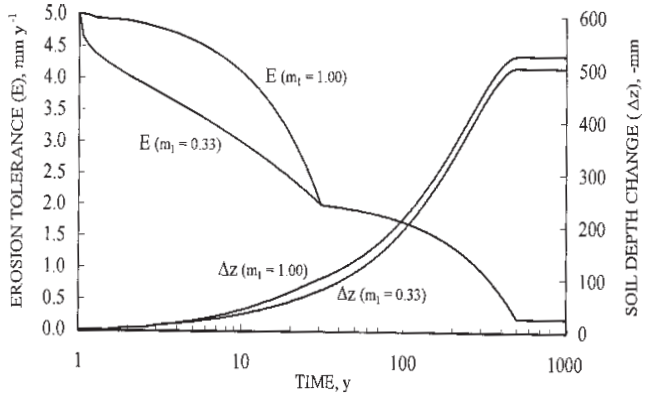

Figure 4 shows an example of erosion tolerance determination considering the following values: E_0 = 5.0 mm y^{-1}, P = 0.2 mm y^{-1}, t_1 = 30 y, E_1 = 2.0 mm y^{-1}, t_2 = 500 y, E_2 = 0.2 mm y^{-1} and different m values, i.e. $m_1 = m_2 = m_3$ = 1.00 in the first case and m_1 = 0.33 and $m_2 = m_3$ = 1.00 in the second.

The erosion tolerance will be the same and in a period of time of 30 years the difference in soil depth change is small. Considering P = 0.2 mm y^{-1} at the end of 100 years Δz = -216 mm and with P = 0.6 mm y^{-1} the Δz = -176 mm with a difference of 40 mm. This difference may not be sufficient to cause substantial productivity losses within this time indicating that the soil formation not necessarily has a great influence on short time decisions. In a longer period of time, in this example 1,000 years, the difference in soil depth change became greater with -124 mm if P = 0.6 mm y^{-1} and -524 mm if P = 0.2 mm y^{-1}. In the case of P = 0.6 mm y^{-1}, soil depth change reaches a maximum of -345 mm after 397 years. After this, soil becomes deeper again since soil formation rate will be greater than soil erosion.

By considering a smaller m_1 value the curve decreased more rapidly, changing significantly the

erosion tolerance values in a short period of time until t_1. However, the soil depth change after 500 y was almost the same indicating a low influence of the short time changes or decisions on irreversible soil degradation due to loss of soil depth for root development.

CONCLUSIONS

The definition of erosion tolerance through time according to the suggested equations allows the use of space-time-dependent variables like soil depth, present erosion rate, present and future social or economic scenarios and support the evaluation of soil degradation via soil depth change. This kind of approach is more appropriate for integrated and quantitative land evaluation procedures and compatible with data analysis by expert systems.

FINAL CONSIDERATION

Aiming the application of equation (9) by interested readers, a Microsoft Excel worksheet is available. To receive a copy of this worksheet, please contact the authors.

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