Temporal Erosion-Induced Soil Degradation and Yield Loss

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ABSTRACT

Intensification of tropical agricultural systems by increasing fertilizer input and technology is a current trend in developing regions. Under intensive management, erosion impacts on crop productivity may not be detected in the short term. However, long-term impacts are expected because erosion rates in tropical agroecosystems are usually greater than the rate of soil formation. A temporal function of soil-depth change was defined and named *life time*. Conceptually, soil's life time is the time until a minimum soil depth needed for sustaining crop production is reached. The life-time function was applied to the Ceveiro watershed (1990 ha) located at the Southeastern part of Brazil, and compared with sugarcane (*Saccharum officinarum* L.) yield loss estimations. Soil erosion prediction was made employing the Water Erosion Prediction Project. The mean soil erosion rate for the area was 15 Mg ha^{-1} yr^{-1}, and sugarcane showed the highest mean value of 31 Mg ha^{-1} yr^{-1}. The half life time of the watershed, i.e., the time until 50% of the area reach the minimum soil depth, was estimated to +563 yr in relation to present time. The estimated time for sugarcane's productivity to be reduced to 50% of the present value (half yield life time) was +361 yr. The life-time function was similar to the estimated long-term impacts of soil erosion on crop productivity. Therefore, the life-time function was considered as an integrative indictor for agricultural sustainability, useful for land-use planning and for the definition of tolerable soil erosion.

The topsoil in high input tropical agricultural systems has been shown to restore yield capacity and biological functions rapidly, even under extremely high erosion rates (Sparovek, 1998; Sparovek et al. 1999). Intensification of agricultural production represented by increasing inputs (especially fertilizers) and improved farm management practices is an established trend for adequately supplying a growing population with food and providing for export resources in most tropical regions (Dyson, 1999). This intensification, combined with the fast topsoil rehabilitation, may counterbalance soil degradation. Thus, erosion-yield estimations for tropical conditions (Lal, 1995; Alfsen, 1996) may result in a too pessimistic prognosis or predict impacts that indeed will not be experienced by the farmers. Extremely high erosion rates, that directly damage the crops or impact yield on a short term have a self-regulating mechanism, i.e., the farmer will naturally invest in erosion control up to the amount he can foresee advantages or prevent short-term productivity loss. The most optimistic scenario would be fertilizers and crop residue additions to the topsoil, genetic enhancement of crop plants and an improved education of farmers being able to compensate erosion effects on crop productivity totally. However, even considering this scenario, erosion rates in tropical agroecosystems are generally much higher than soil formation. If erosion surpasses soil formation the agricultural system can not be defined as sustainable, once an essential natural resource with unknown substitute, i.e., the fertile topsoil, is exhausted in a predictable future.

Stamey and Smith (1964) first suggested to define tolerable erosion rates as a function of the available soil resources. They stated that the fertile topsoil could be consumed by erosion until a defined minimum amount would be available. This minimum amount should be sufficient to guarantee efficient crop production. Later, Skidmore (1982) developed this concept mathematically as a function of the remaining soil depth. With current erosion prediction technologies, erosion rates can be estimated with good precision and the soil depth can be easily measured. Despite some contradiction about absolute values (Owens and Watson, 1979; Alexander, 1988; Wakastsuki and Rasyidin, 1992; Heimsath et al., 1997) soil formation in most agricultural systems is very low in comparison with usual erosion rates. Soil's depth, erosion, and formation rates are the main variables needed to calculate soil-depth change over time. That way, soil-depth change can be expressed as a temporal function, which can be handled as a spatial variable using erosion prediction models and a Geographic Information System (GIS). The basic mathematical development of the time concept and its application for the estimation of tolerable erosion rates were first suggested by Sparovek and de Jong van Lier (1997). According to this concept, the impact of soil erosion on crop yield can be predicted as a function of time. This particular time was defined as life time by Sparovek et al. (1997). Crop yield can also be described as a function of the remaining soil depth (Salviano et al., 1998), therefore converted into an analogous temporal function.

The objective of this paper is to compare the life-time concept with a temporal function of yield loss due to soil erosion. The study area is representative for Brazilian sugarcane production and consists of the Ceveiro watershed. The adequacy of the life time as a proxy for the definition of soil loss tolerance and for the assessment of erosion impacts on crop productivity is also discussed.

MATERIALS AND METHODS

The Study Area and Erosion Modeling

The Ceveiro watershed (1990 ha) is located at the Southeastern part of Brazil (Piracicaba) with central coordinates of 22°38′54″S and 47°45′40″W. The climate, according to Koep-

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Abbreviations: GIS, Geographic Information System; WEPP, Water Erosion Prediction Project.

Table 1. Soil types and occurrence in the Ceveiro watershed.

Soil type (soil taxonomy)	Area	Occurrence
	ha	%
Typic Udorthent	904	45.3
Arenic Paleudult	384	19.3
Typic Paleudalf	240	12.0
Typic Paleudult	86	4.3
Typic Eutrochrept	71	3.6
Psammentic Paleudult	61	3.1
Arenic Paleudalf	57	2.9
Rhodic Paleudalf	40	2.0
Arenic Endoaquult	22	1.1
Typic Dystrochrept	22	1.1
Mollic Paleudalf	22	1.1
Typic Udipsamment	20	1.0
Alluvium	8	0.4
Typic Kandiaqualf	8	0.4
Urban	39	2.0
Water Reservoir	6	0.3
Total	1990	100

pen's classification, is Cwa i.e., humid subtropical with a dry winter and <30 mm of rain in the driest month, the temperature in the hottest month is in excess of 22°C and in the coldest below 18°C. The landscape is usually composed of S-shaped profiles and the mean slope value is 13% (minimum slope 0.02%, maximum 59.03%, and 90% of the values between 2.42 and 25.98%). The soil types found in the area, their classification according to U.S. soil taxonomy (Soil Survey Staff, 1990), and their occurrence are shown in Table 1. In recent years no significant land-use changes have been observed, so the available data for land-use for 1995 composed of sugarcane (66.3%), pastures (13.9%), forests (17.4%), corn (0.1%), and nonagricultural use (2.3%) were used for soil erosion calculations. Soil erosion and depositions were calculated using the Water Erosion Prediction Project (WEPP) hillslope version 99.5 (Flanagan and Nearing, 1995). Slope information was extracted from a topographic contour map scale 1:10 000 with an original vertical resolution of 5 m, interpolated to 2 m vertical resolution using GIS triangulation tools. Soil-erosion estimation transects following the surface runoff outflow were defined for WEPP calculations (939 transects with a mean length of 243 m distributed uniformly over the entire area). The altitude values were converted into relative slope values by means of an interface program for building the slope input files for WEPP. Local climatic data from daily 30 yr records was used to calculate climate inputs. The climate input file for WEPP was generated using CLIGEN ver. 4.3. (Nicks et al., 1995) running a 100 yr simulation. Soil input files were calculated for each soil types using the equations suggested by Flanagan and Nearing (1995) based on soil analysis results of 223 sampling points. Management files for sugarcane, corn, pasture, and forest were computed following the methods described by Flanagan and Nearing (1995). The input parameters were adjusted to represent local crops, pasture management, and the forest parameters. The GIS procedures were carried out by means of TNTmips (Micro Images) version 6.2. Soil-loss values were calculated for each intersection point of the transects with the contour line map (a total of 11 238 points or ~6 points ha^{-1}) and interpolated to a raster format (pixel of 10 by 10 m) by Kriging using a spherical variogram. The variables used for simulations, their description and sources are shown in Table 2.

The Life Time Calculation

The soil-loss or deposition values expressed in kg m^{-2} yr^{-1} were converted in m yr^{-1} using a constant density value of 1200 kg m^{-3}. The soil depth was measured in field surveys by augering from the surface down to the C horizon or consolidated rock. In all, 250 points were sampled for depth measurement. The depth values were interpolated to raster format (pixel of 10 by 10 m) employing Kriging and a spherical variogram. Soil formation was considered constant, with a rate of −0.0002 m yr^{-1} based on the value suggested by Skidmore (1982). Following the suggestions of Stamey and Smith (1964), Skidmore (1982), and Sparovek and de Jong van Lier (1997) a minimum soil depth was defined, representing the depth limit to which soil may be consumed. When the minimum depth is reached, soil loss has to be equal or less than soil formation avoiding further depth decrease, which would have the consequence of irreversible degradation. The minimum soil depth was considered as constant with a value of 0.2 m according to suggestions of Salviano et al. (1998) who established crop-yield and soil-depth relations in the same region and similar soils. Based on these variables, the life time was calculated according to Eq. [1]:

$$LT = \frac{SD - SD_{min}}{\frac{SL}{D_s} + SF} \quad [1]$$

in which: LT equals life time (yr), SD equals present soil depth (m), SD_{min} equals minimum soil depth (0.2 m), SL equals soil erosion (+soil loss −soil deposition, kg m^{-2} yr^{-1}), D_s equals

Table 2. Description of the variables used for simulations.

Variable	Source/Description	Reference
Erosion Prediction		
Model	WEPP applied to 11 238 points	Flanagan & Nearing (1995)
Soil map	Field survey	
Land use	Aerial photographs from 1995 supplemented with field survey	
Topography	Digital contour map at scale 1:10 000	
Climate	Recent 30 yr of local daily records converted to WEPP input files using CLIGEN ver. 4.3.	Nicks et al. (1995)
WEPP soil input files	Based on samples from 223 profiles analytical data (very fine sand, sand, clay, organic matter, cation-exchange capacity, rocks, and soil depth)	Flanagan & Nearing (1995)
WEPP management input files	Based on local crop data	Flanagan & Nearing (1995)
Life time calculation		
Model	Eq. [1]	
Soil depth	Field measurements on 250 points	
Soil formation	Constant value of 0.0002 m yr^{-1}	Skidmore (1982)
Minimum soil depth	Constant value of 0.2 m	Salviano et al. (1998)
Crop yield		
Yield-soil depth relation	Equation adapted from local field experiment data	Salviano et al. (1998)

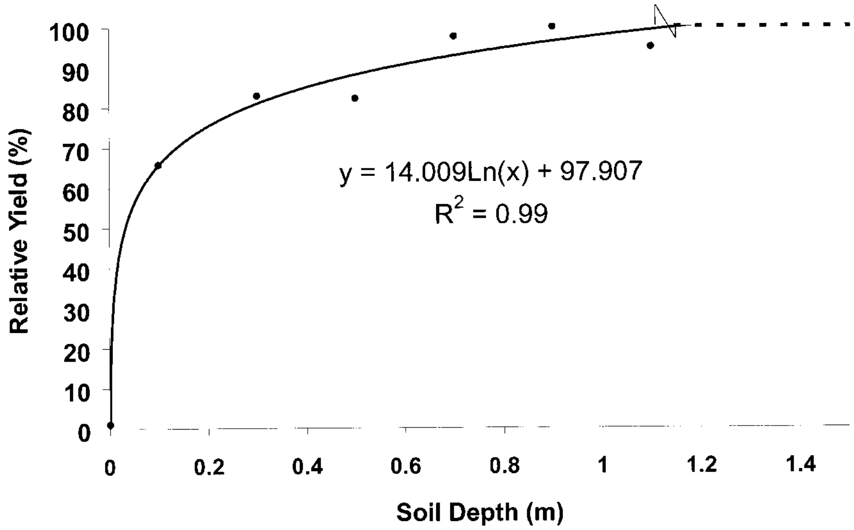

Fig. 1. Relation between relative yield of *Crotalaria juncea* and soil depth.

soil bulk density (1200 kg m^{-3}), SF equals soil formation (-0.0002 m yr^{-1}; -0.24 kg m^{-2} yr^{-1}), restrictions LT ≥ 0 and SD $\geq$ SD$_{min}$.

The life time represents the time needed for a certain soil to reach a minimum soil depth, so, negative values can not be accepted. Therefore, Eq. [1] has some restrictions for calculating LT. When Eq. [1] results in a negative LT value because SL/D_s < |SF| or SL < 0 LT value should be considered as equal to + ∞. Another restriction for estimating the LT by Eq. [1] is the condition SD < SD$_{min}$. In this case, the minimum soil depth has been reached and LT is taken to be zero.

Soil Erosion and Crop Yield

Although sugarcane is the main crop in the region, no soil-depth-yield data was available for this crop. Salviano et al. (1998) determined that there was a significant relationship between relative yield of *Crotalaria juncea* (a green-manure crop used in rotation with sugarcane) and the remaining soil depth for a Ultisol in the same region as the Ceveiro watershed is located. The experiment was conducted on a commercial field cultivated with sugarcane for at least 60 yr. This data was used to represent the soil-depth-yield function because of its direct relation of soil depth to yield (rather than soil erosion to yield as it is more usual) and because of the same climatic and soil condition as observed in the study area. The original data determined by Salviano et al. (1998) was used to calculate a regression equation relating relative yield and remaining soil depth as shown in Fig. 1. This equation was used to calculate the relative yield values for sugarcane in the range of 0 to 100% corresponding to a soil depth from 0 to 1.0 m. With soil depths greater than 1.0 m the relative yield was considered to be 100%. The relative yield values were calculated for the present time up to +1000 yr (present time, +25 yr, +50 yr, +100 yr, +200 yr, +300 yr, +400 yr, +500 yr, +600 yr, +700 yr, +800 yr, +900 yr, +1000 yr).

RESULTS AND DISCUSSION

The soil erosion data interpolated from the 11 238 estimation points had a mean value of 15 Mg ha^{-1} yr^{-1} (lowest value of -250 Mg ha^{-1} yr^{-1}, highest value of +160 Mg ha^{-1} yr^{-1} and 90% of the values were between -100 and +101 Mg ha^{-1} yr^{-1}). Deposition (negative soil erosion values) were observed in 22% of the area and positive erosion values or soil loss in the remaining 78%. Most of the deposition occurred in the forests along the rivers located on the smoother sloped floodplains (Fig. 2). Large and uninterrupted areas of low soil-loss values of ~0 to 2 Mg ha^{-1} yr^{-1} were only observed for pastures and forests. In most sugarcane areas soil loss from upper slope positions was initially low but increased downslope. Extreme high rates of soil loss was observed at the backslope and footslope positions. An abrupt boundary was observed between erosion and deposition that corresponded to the edge of the riparian forest.

The mean soil depth for the Ceveiro watershed was 0.97 m (minimum 0.21 m; maximum 5.06 m; 90% of the values between 0.56 and 1.38 m). A SD$_{min}$ value of 0.2 m was used for life-time calculations, consequently no zero life-time values were obtained in this case. The life-time map for the area calculated according to Eq. [1] is shown in Fig. 3. The gray areas correspond to one of both conditions that life time results in + ∞ (SL/D_s < |SF| or SL < 0). According to the definition of life time these areas will remain productive for an infinite period of time because the condition SD < SD$_{min}$ will never be achieved. The other areas of the map, with colors ranging from dark red (worst condition with short life time) to yellow (good condition with long life time), will eventually reach the minimum soil depth of 0.2 m. The SD$_{min}$ value indicates the soil depth beneath which irreversible degradation is foreseen and no conventional agronomic technology or improvement is expected to compensate yield lost. Thus, the life time (per definition the time to reach the condition SD = SD$_{min}$) also indicates the urgency for soil conservation improvement or land-use change to more protective crops. The spatial pattern of life time (Fig. 3) is similar to the one for soil erosion (Fig. 2). The significance of specific soil erosion rates may be difficult for farmers and decision makers to understand and fixed erosion tolerance values are far from being a consensus matter. In contrast, the life-time concept evaluates soil degradation using an easy to understand indicator, i.e., the condition SD = SD$_{min}$

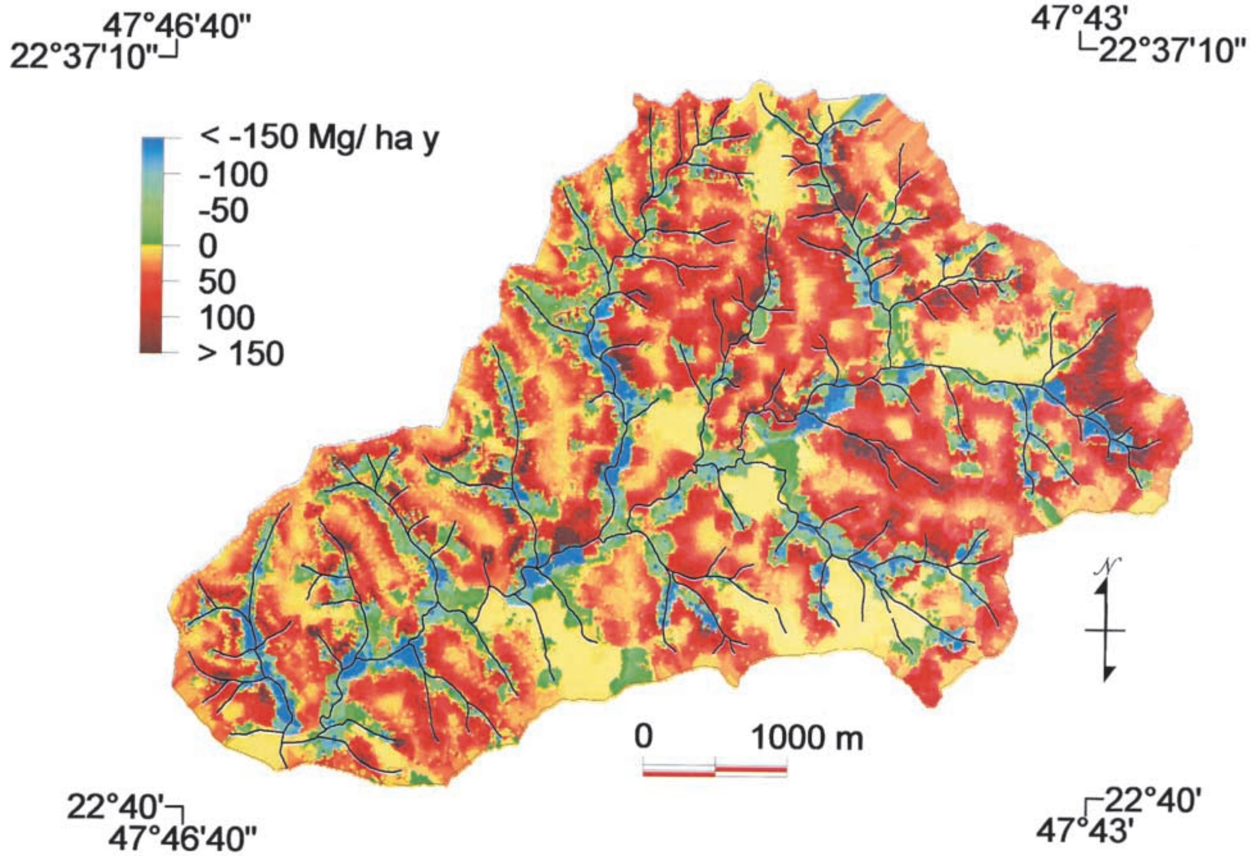

Fig. 2. Soil erosion and sediment deposition map for the Ceveiro watershed.

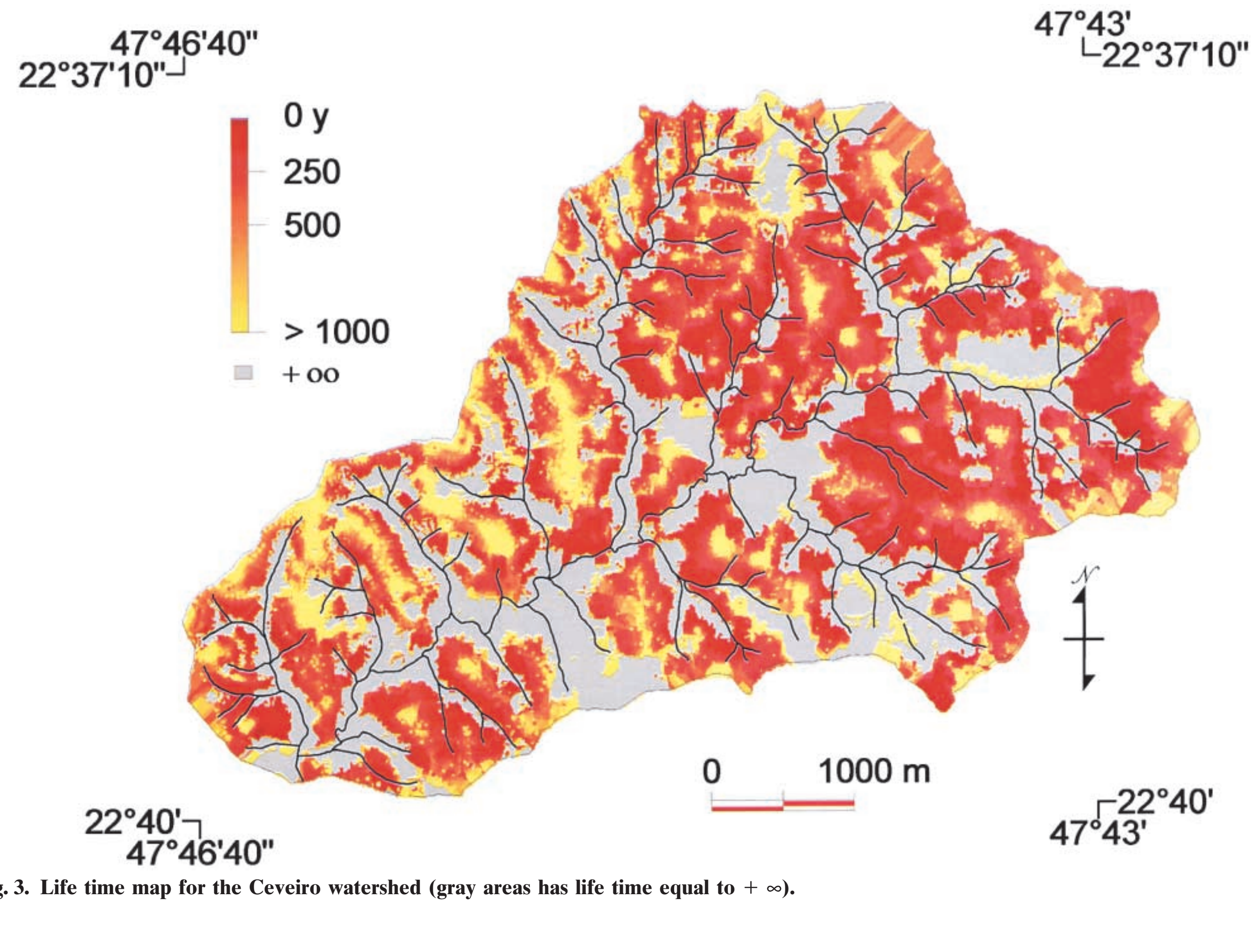

Fig. 3. Life time map for the Ceveiro watershed (gray areas has life time equal to + ∞).

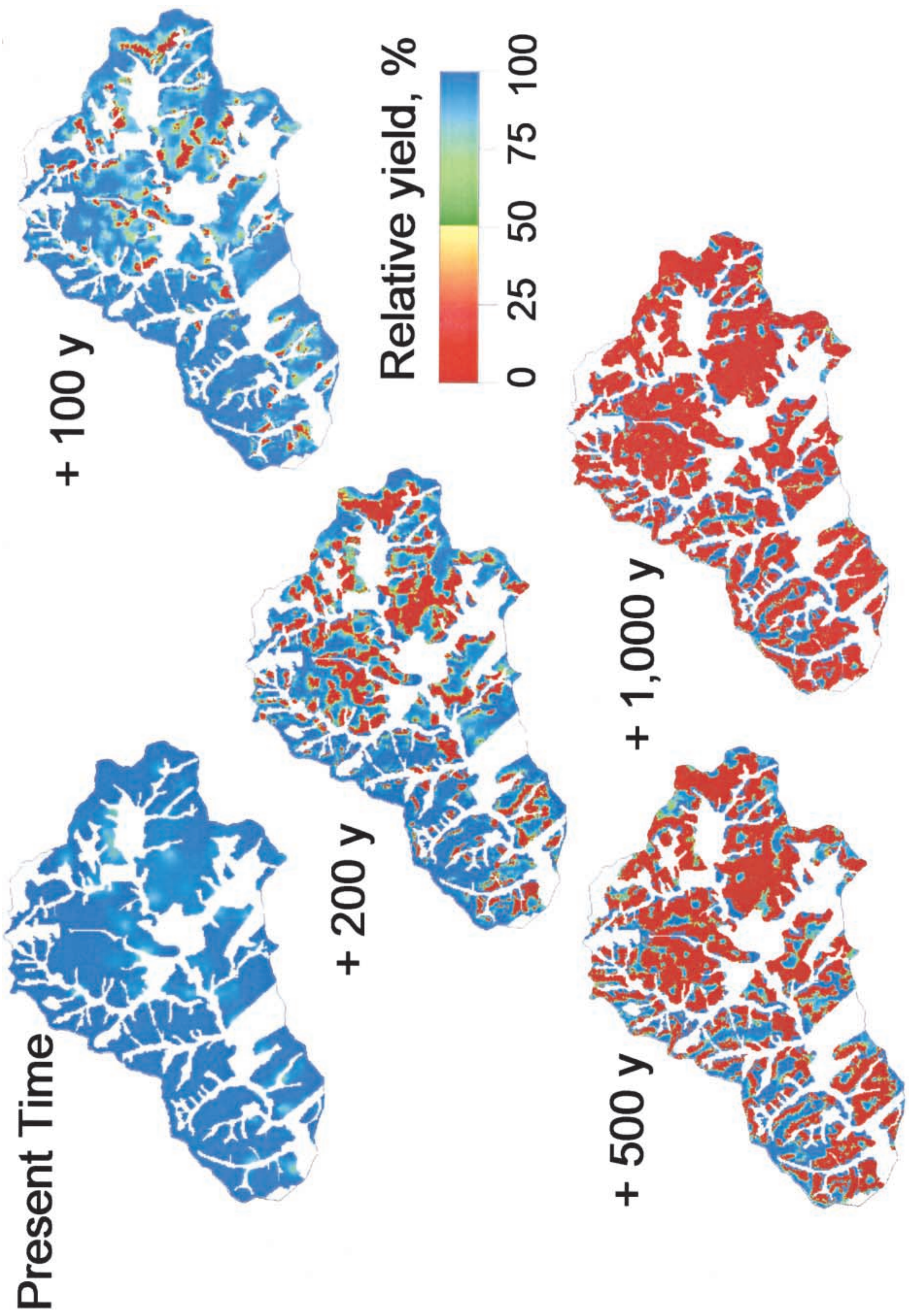

Fig. 5. Sugarcane relative yield maps as a function of time for the Ceveiro watershed (white areas are nonsugarcane land-uses).

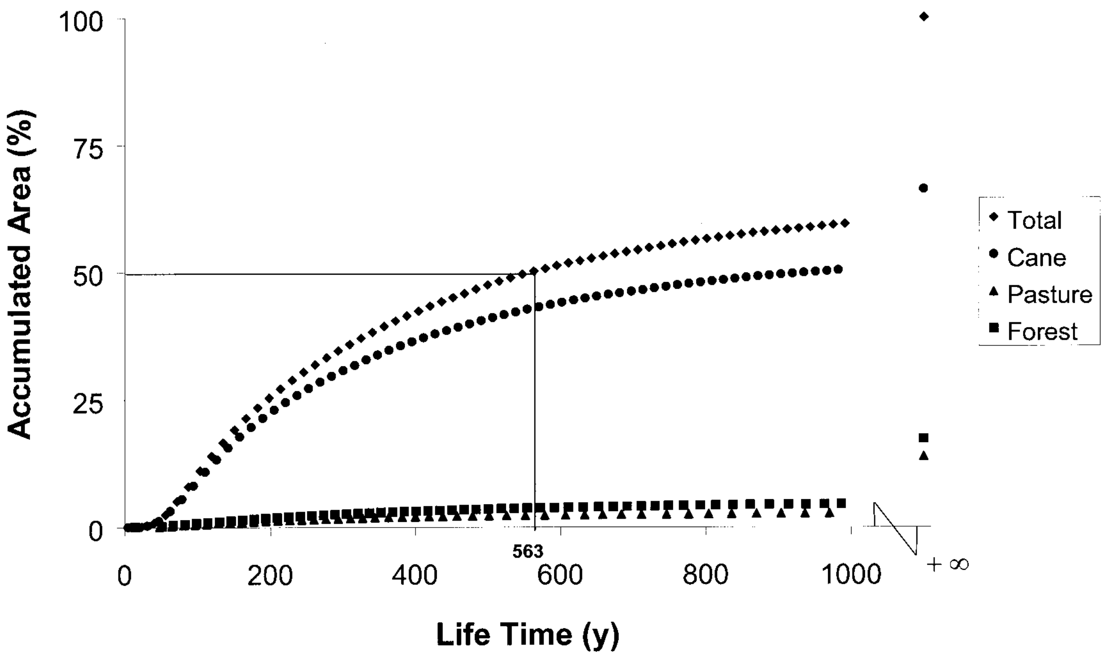

Fig. 4. Accumulated area relative to the watershed of the land-use types in relation to the life time (condition SD = SD_{min}) for the Ceveiro watershed.

(end of life). Independent on how efficient the agronomic technology may be, from that time on not enough soil will be available to sustain crop production and the degradation process will be irreversible. Crop production on the soil will be impossible. Time and life are easy concepts to understand and the basic ideas of the life-time function to evaluate soil degradation. An implicit restriction of life time is its exclusive on-site approach. The life-time function does not reflect off-site erosion impacts.

A quantitative interpretation of the data shown as a map in Fig. 3 is shown in Fig. 4. In this graphic, the accumulated area, expressed as percentages of total watershed area, is related to increasing values of life time.

Large (+ ∞) uninterrupted life-time areas were evident (Fig. 3), most of them being associated with pastures and forests. The northern and especially the western part of the area had the highest life-time values.

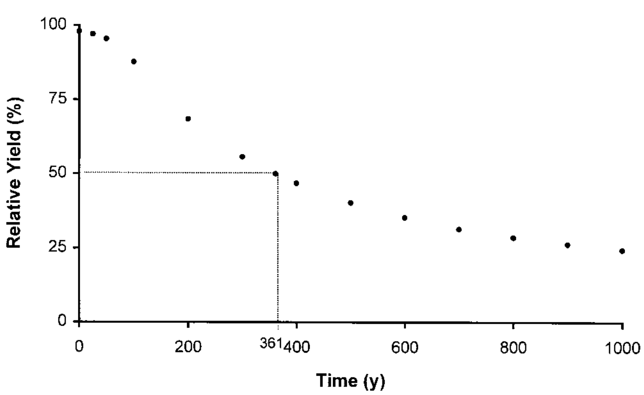

Fig. 6. Mean sugarcane relative yield as a function of time for the Ceveiro watershed.

Deeper soils in these areas are probably the main reason for longer life time. With current land-use, soil depth was estimated to increase (+ ∞ life-time values) on 30% of the total watershed. Soil depth increases occurred in two conditions. The first is $SL/D_s < |SF|$ or lower soil erosion rate than soil formation. This condition, corresponding to $0 \leq SL < 2.4$ Mg ha^{-1} yr^{-1}, occurred on 8% of the watershed. The second condition, where $SL < 0$ (soil is being deposited), represented the other 22%. The usefulness of this method as a land-use planning tool can be demonstrated by an example where we calculated the life time considering a scenario where the entire watershed were pasture. In this scenario, the infinite life time area would increase to 87% (81% $SL/D_s < |SF|$ and 6% $SL < 0$). With current land-use, life time equal to positive infinity occurred on 14% of sugarcane lands, 68% of pastures, and 62% of the forests. For sugarcane the mean erosion rate was estimated to 31 Mg ha^{-1} yr^{-1} and the relative area with soil loss (87%) was much greater than the area of sediment deposition. In current pastures the relative area with soil loss (61%) was also greater than the sediment trapping regions, but the mean erosion value was negative (−13 Mg ha^{-1} yr^{-1}). More than half of the area currently under forests (51%) was trapping sediment and the mean deposition rate was −25 Mg ha^{-1} yr. The negative average soil loss rates in pastures and forest lands reflects deposition of sediment eroded from sugarcane lands.

The watershed life-time curve (Fig. 4) showed to be relatively stable in the near future (from current time up to ~ +50 yr) but after that degradation is predicted to increase rapidly until ~ +400 yr. The number of years until 50% of the watershed's area to reach the minimum soil depth was estimated to +563 yr. This time was

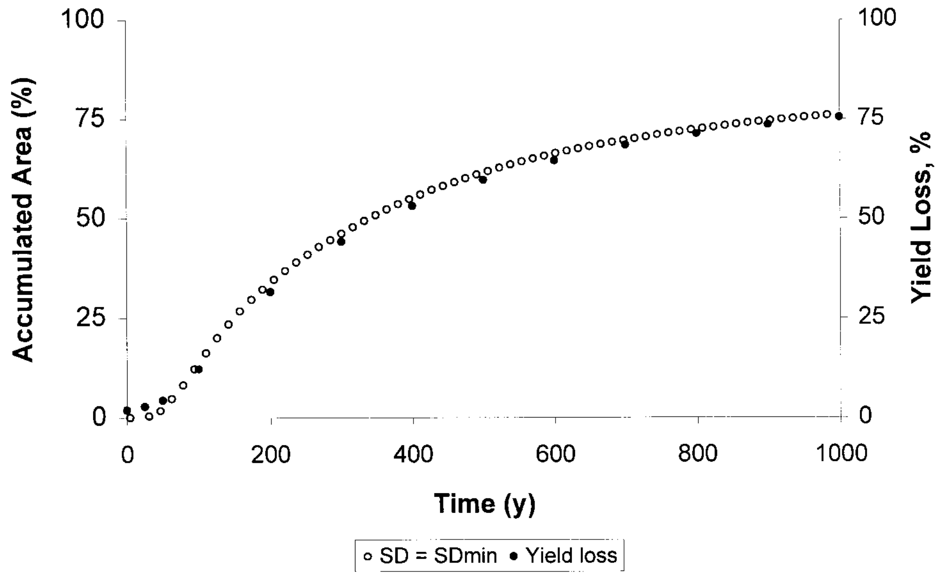

Fig. 7. Sugarcane relative yield loss and accumulated area with soil depth equal to minimum depth (life time) as a function of time for the Ceveiro watershed.

denominated the half life time. The half life time is suggested as a good integrative indicator to compare different areas, expressing its mean soil degradation potential in a single number.

With current land-use, the estimated yield loss because of soil-depth decrease had the particular distribution pattern shown in Fig. 5. Because the relative yield-soil-depth curve (Fig. 1) declines rapidly for soil depth <0.5 m, intermediate relative yield values (between the two extremes of 0 to 100%) are rare, when applying this equation to soil-depth decrease with time. Uninterrupted areas with 0 or 100% relative yield can be observed in the maps. The 0% relative yield spots grow from the borders into the productive area of 100% of relative yield. The sectored, rather than scattered, development of soil degradation maintains the spatial continuity essential for large scale sugarcane farming. It may also make it easier to promote land-use changes to other production systems such as pastures when some parts of the area become unsuited or economically unattractive for intensive cropping. At present time this trend can be observed on a more regional scale.

The relative yield vs. time curve for sugarcane (Fig. 6) showed an approximately constant value until ~+50 yr, after that declining rapidly and reaching 50% of relative yield at +361 yr. This time, in analogy named half yield life time, is another integrative indicator that can be used to represent the sugarcane yield loss because of soil erosion for the entire production area in a single number. The relative sugarcane average yield at +1000 yr was estimated in 25% and the areas still productive at that time are spatially coincident with the areas with high or infinite life time values.

The life time and the yield loss for sugarcane production in watershed was represented in the same graph (Fig. 7). Both are functions of the remaining soil depth resulting form soil erosion over the time. Consequently, a similar trend can be observed.

CONCLUSIONS

Considering that increasing inputs and technology may temporarily rehabilitate the soil surface layer faster than it can be degraded by soil erosion, the life-time concept is presented as a reasonable proxy for estimating long-term erosion impacts on crop yield. For life-time calculation, only the field survey variable soil depth is needed in addition to those required for soil-erosion estimation. Combining this information with a soil-depth/crop-productivity function allows the sustainability of land-use to be determined. Because the life time of a soil is based on easily determined information, makes its application for developing regions more feasible.

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Organic Matter Dynamics and Carbon Sequestration Rates for a Tillage Chronosequence in a Brazilian Oxisol

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ABSTRACT

Amounts and rates of C sequestration under no-tillage are not known for a major ecological region of south Brazil. These were assessed in a Brazilian Oxisol under a plow and no-tillage chronosequence located in Paraná State. The chronosequence consisted of six treatments: (i) native field (NF); (ii) 1-yr plow conversion of native field to cropland (PNF-1); (iii) no-tillage for 10 yr (NT-10); (iv) no-tillage for 20 yr (NT-20); (v) no-tillage for 22 yr (NT-22); and (vi) conventional tillage for 22 yr (CT-22). Soil samples were collected from five depths. No-tillage, compared with the NF treatment, caused a significant increase in soil organic C (SOC) storage. More than 60% of this increase occurred in the 0- to 10-cm soil layer. There was a decrease in the amount of SOC in the CT-22 compared with the NF soil treatment and 97% of this loss also occurred in the 0- to 10-cm layer. There was a close relationship between the SOC content and the amount of crop residues input ($R^2 = 0.74$, $P \leq 0.05$). There were increased SOC concentrations in the finer particle-size fractions (<20 μm) of no-tillage surface soil compared with the NF or CT-22 soils. However, the percentage of SOC derived from crop residues in no-tillage treatments, as assessed by 13C natural abundance (δ), was generally greater in the coarse (>20 μm) than in the finer (<20 μm) particle-size fractions. The C sequestration rate for no-tillage was 80.6 g C m^{-2} yr^{-1} for the 0- to 20-cm depth and 99.4 g C m^{-2} yr^{-1} for the 0- to 40-cm depth. The no-tillage C sequestration potential for South Brazil was estimated as 9.37 Tg C yr^{-1}.

The SOC pool in the top 1-m depth of world soils ranges between 1462 and 1576 Pg. It is nearly three times that in the aboveground biomass and approximately double that in the atmosphere; 32% of this is contributed by soils in the tropics (Eswaran et al., 1993; Lal et al., 1995; Batjes, 1996).

Agricultural practices can render a soil either a sink or a source of the atmospheric CO_2, with direct influence on the greenhouse effect (Lugo and Brown, 1993; Lal et al., 1995). The CO_2 contribution to radiative forcing is about 50%, and 22.9% of total CO_2 emissions to the atmosphere is attributed to agriculture, deforestation, and land use (Intergovernmental Panel on Climate Change, 1996).

In temperate zones, grassland soils tend to lose 30 to 50% of their original SOC content in the first 40 to 50 yr of cultivation (Campbell and Souster, 1982; Mann, 1985). In contrast, the SOC loss in tropical regions may be several times higher (Lal and Logan, 1995). In Northeast Brazil, Resck (1998) reported a SOC loss of 69% within 5 yr of cultivation by a heavy disk harrow in quartz sand (<15% clay content) and 49% in a Typic Hapludox—Dark Red Latosol (>30% clay content). Plowing decreases aggregate stability, disrupts macroaggregates and exposes SOC to microbial processes (Tisdall and Oades, 1982). As a consequence, the mineralization rates increase due to high aeration, resulting in high CO_2 flux to the atmosphere (Elliot, 1986; Reicosky et al., 1995).

Several reports have shown that crop residue mulch associated with no-tillage management improves soil aggregation and increases SOC content (Havlin et al., 1990; Carter, 1992; Cambardella and Elliot, 1992, 1993). However, this increase is generally restricted to the surface soil. Kern and Johnson (1993) reviewed data from 17 field studies comparing no-tillage with conventional-tillage plots in the USA, and observed that SOC gains

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Abbreviations: CT-22, conventional tillage for 22 yr; NF, native field; NT-10, no-tillage for 10 yr; NT-20, no-tillage for 20 yr; NT-22, no-tillage for 22 yr; PNF-1, 1-yr conversion of native field to cropland by plow tillage; SOC, Soil organic C; TN, total nitrogen; δ, natural abundance; *,**,***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.