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# Soil loss tolerance in the context of the European Green Deal

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A B S T R A C T

Soil erosion by water, and the consequent loss of a non-renewable resource, is a relevant environmental issue which has economic, ecologic, and social repercussions. In the context of the European Green Deal, the increasing awareness of soil Ecosystem Services is leading to give the due relevance to this problem. Notwithstanding the recent soil conservation strategies adopted by the Common Agricultural Policy had positive effects, the concern regarding this topic is drastically increasing for the normalization of extraordinary rainfall events due to climate change. Recent events occurred in Europe demonstrated that landscape protection is often inadequate and interventions to prevent damages due to hydrogeological instability are scarce.

The determination of a "tolerable" soil loss *TSL* is useful to establish a quantitative standard to measure the effectiveness of strategies and techniques to control soil erosion. However, soil conservation strategies/works designed by the mean annual value of the climatic variable, as the rainfall erosivity factor *R*, are not appropriate for some erosive events which produce intolerable sediment yield values. Therefore, the adoption of an adequate *TSL*, which could help to ensure the protection of soil functions and a sustainable soil use, should be a primary goal to reach for policy makers.

In this paper, a new method to define the tolerable soil loss is proposed. This approach is based on the statistical analysis of the measured annual values of *R* and leads to the determination of the cover and management factor for which the maximum tolerable soil loss is equal to the annual soil loss of given return period. The analysis demonstrated that to limit soil erosion to the tolerable soil loss, interventions to change land use, reduce field length or apply support practices can be carried out.

## 1. Introduction

Soil loss by water erosion becomes a cause of soil productivity reduction if the rate of soil loss exceeds that of soil formation. Geological erosion, which is characterized by an erosion rate less than the formation rate, would not reduce soil productivity. Accelerated erosion, induced by human activities, becomes a desertification threat [1].

The soil thematic strategy of the European Commission [2] established that "*soil is essentially a non-renewable resource and a very dynamic system which performs many functions and delivers services vital to human activities and ecosystems survival*". The soil formation processes are very slow, requiring from hundreds to thousands of years to form few centimetres of topsoil under normal agricultural condition [3,4]. Soil erosion is more than soil formation across the European Union and the amount of soil lost by water erosion

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produces an estimated economic loss, calculated assuming a restoration cost of $20 per tonne, almost equal to $20 billion per year [5]. Joint Research Centre (JRC) estimated that in Europe soil erosion affects over 12 million hectares of land and leads to €1.25 billion loss in crop productivity [6].

Notwithstanding soil conservation strategies adopted by the Common Agricultural Policy, in the period 2000–2010, reduced soil loss by 20% in cultivated areas, the concern regarding this topic is drastically increasing due to normalization of extraordinary rainfall events, as those recently occurred in Luxembourg and Germany, which are becoming more and more ordinary. These natural events demonstrated that landscape protection is often inadequate and interventions to prevent damages due to hydrogeological instability are scarce.

Soil conservation strategies prevent both agricultural productivity losses in the area which is potentially interested by soil loss ("on-site" effects) and limit indirect effects ("off-site") which can occur along the flow paths due to sediment delivery (e.g., reservoir silting). Therefore, the restriction of soil erosion processes preserves the production of agriculture and forestry, limits the use of fertilizers and other auxiliary substances and thus allows an environmentally friendly use of soil [7,8].

Prevention of soil erosion is an important regulating service for whose quantitative definition different methodological approaches were used: 1) overlaying of potential soil erosion (or risk) map with a vegetation map to estimate the ability of the ecosystems to prevent or mitigate soil loss in risk areas [9–11]; 2) estimation of the effects of soil erosion strategies using models to calculate the difference between potential and actual soil loss [3,12–14] direct use of the soil loss value [15–19]; 4) estimation of the fraction of the examined area in which erosion problems do not occur [20]; 5) percentage of vegetation cover in the investigated area [16,17] or a vegetation cover index [21–23].

The European Green Deal is a complete strategy to take on climate and environmental-related challenges in which soils have a main role to reach the sustainable development goals expected for 2030 [24,25]. The package of measures proposed by the European Commission (Biodiversity Strategy 2030, the "Farm to Fork" and the European Climate Law) include actions also finalized to a sustainable soil management which preserves soil quality and limits soil contamination. Degradation processes of agricultural soils must be seriously considered to preserve soil health in Europe bearing in mind that soil loss by water erosion processes is two times greater than soil formation rates in European agricultural lands [25,26].

Estimation of land degradation costs [27] is generally carried out considering productivity loss due to soil erosion. This 'first-order' cost evaluation focuses simply on agricultural production losses [28–30] and the economic value of land productivity loss is estimated by the loss in crop production (tonnes) multiplied by the average market price ($/tonnes). This approach neglects the 'second round' which takes into account other effects beyond the primary resource as the land factor.

The Ecosystem Services (ES) are related to the main ecosystem processes (such as water regulation, soil loss, pesticide control and life cycle maintenance) and are associated to the need of mitigate the impacts from current and future environmental hazards [23]. Considering that soil ecosystem provides many services, a holistic assessment framework, useful to establish the economic value of soil Ecosystem Services (ES), is required. Furthermore, no shared framework for the classification and economic valuation of soil ES [31] is available.

Payment for ecosystem service (PES) continue to attract attention of scholars and stakeholders as efficient tool to encourage environmental conservation strategies [32–35]. PES represents a cost associated with more environmentally friendly land use and can be considered as a tool to compensate for less crop productivity to assure an environmental service. The spatial targeting, which is to establish where to pay, is one of the greatest challenges of PES application [36]. Adopting a spatial targeting means selecting the most suitable areas for implementing PES policies with the aim to improve their effectiveness and efficiency at the applied spatial scale.

The amount of average annual soil loss, expressed as t ha$^{-1}$, can be considered a disservice related to soil use; to limit soil loss to a tolerable value, an ecosystem service associated with the protective effect against soil loss should be implemented. To quantify this protective effect, a soil loss target value has to be selected to measure the positive ecosystem service (i.e., soil loss equal to or less than target value).

In this context, the concept of Tolerable Soil Loss *TSL*, also named soil loss tolerance, is useful to assess the threat of productivity loss and off-site damages [37]. Soil loss tolerance is also a useful criterion to design soil erosion control works and apply conservation practices or to be used as a soil quality indicator [38,39].

The idea to establish a tolerable soil loss, *TSL* [40,41], is related to the need of soil conservationists to establish a quantitative standard to measure the effectiveness of strategies and techniques to control soil erosion. In 1961 and 1962, the American Soil Conservation Service organized six workshops, attended by agronomists, geologists, and soil conservationists, with the aim to define regional soil loss prediction values. The result of this sharing action was the definition of a value of 5 tons acre$^{-1}$ year$^{-1}$ as maximum tolerance. A widespread application of *TSL* started in 1962 when the U.S. Soil Conservation Service defined the soil loss tolerance as "*the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely*" and proposed *TSL* values, ranging from 4.5 to 11.2 t ha$^{-1}$year$^{-1}$, for many American soils [42–44].

Even if the original definition of soil loss tolerance is exclusively related to the effects on crop production, many other negative effects can be included into *TSL* definition. For this reason, a two-levels definition was proposed by Larson [45] in which the lower limit $TSL_1$ allows to maintain the aimed on-site soil productivity while the upper limit $TSL_2$ is associated to the need of limiting off-site effects such as water pollution, gully erosion and reservoir sedimentation.

Europe's environment assessment [46] considered that *TSL* varies with soil depth, soil type, and climatic conditions and suggested a range between 1 t ha$^{-1}$ year$^{-1}$ for shallow sandy soils and 5 t ha$^{-1}$ year$^{-1}$ for deep well-developed soil. Anyway, when the soil formation rate is low any annual soil loss value greater than 1 t ha$^{-1}$ year$^{-1}$ can be considered capable to determine irreversible soil quality damage in a period of 50–100 years.

At the present level of scientific knowledge, tolerable soil loss values ranging from 0.3 to 2 t ha$^{-1}$year$^{-1}$ are adopted in Europe and this variability is related to the driving factors of soil formation. Huber et al. [47] proposed to adopt higher *TSL* values for southern Europe than for northern Europe. The European Commission [2] suggested to the Member States to adopt *TSL* values adequate to ensure the protection of soil functions and sustainable soil use. To the best of our knowledge, only two European countries adopted specific values of tolerable soil loss. In Switzerland, the *TSL* value ranges from 1 to 2 t $ha^{-1}$ $yr^{-1}$, while Norway uses 2 t $ha^{-1}$ $yr^{-1}$ [48].

The Organisation for Economic Co-operation and Development (OECD) suggested a soil erosion rate lower than 6 t $ha^{-1}$ $year^{-1}$. Bazzoffi [4] proposed a soil loss tolerance value, named Environment Minimum Requirements (EMR), which derives from the compromise to reduce soil erosion rate and to ensure the agricultural land use in the area. The EMR values listed by Bazzoffi [4] never exceed 3 t $ha^{-1}$ $year^{-1}$, which is half of that proposed by the OECD. A list of soil loss tolerance values is reported in Bazzoffi [4] and Di Stefano and Ferro [49].

The adoption of adequate *TSL* values is necessary, especially in a climate change scenario in which the occurring frequency of extreme rainfall events is increased. In this paper, a new method to estimate soil loss tolerance at a regional scale is presented. The proposed approach applies a revised estimate of *TSL*, based on the application of the USLE, and uses the cover and management factor for which the annual soil loss of given return period occurs.

## 2. Methodology

According to Toy et al. [50] soil loss tolerance concept is a useful conservation-planning tool in which technical and nontechnical elements are joined and expressed by a single number.

Wischmeier and Smith [42] proposed to use the Universal Soil Loss Equation (USLE) combined with the *TSL* value (t $ha^{-1}$ $year^{-1}$) for establishing soil conservation strategies or to design works:

$$\frac{TSL}{R\ K\ S} = L\ C\ P \quad (1)$$

in which *R* is the mean annual value of the rainfall erosivity factor, *K* is the soil erodibility factor, *S* is the slope steepness factor, *L* is the slope length factor, *C* is the cover and management factor and *P* is the support practice factor. Eq. (1) establishes that *L*, *C* and *P* factors can be modified for obtaining a soil loss value equal to the tolerable soil loss *TSL*.

Soil conservation strategies/works designed by the mean annual value of the climatic variable, as the rainfall erosivity factor, could allow for a suitable erosion control in most years in which small erosive events occur while are ineffective respect to relevant erosive events, which can produce intolerable sediment yield values [51,52]. Many Authors [53,54] suggested that conservation strategies should be designed considering large storms rather than average climatic conditions. Historical sequences of soil loss measurements, having a sufficient sample size, should be used to carry out a frequency analysis and to estimate the soil loss having a given return period [55,56]. As an example, Larson et al. [57] proposed to design conservation systems for limiting soil loss using a target value corresponding to a return period variable from 10 to 20 years.

Use of a soil loss value of given return period to design soil conservation systems is uncommon as the frequency analysis, which requires a reliable number of measurements, is rarely applied in soil erosion studies [53,55,56,58–60].

Bagarello et al. [60], using soil loss measurements carried out on plots of different length, λ (11, 22, 33 and 44 m) at the experimental station of Sparacia (southern Italy), carried out an investigation on statistical distribution of soil loss. Bagarello et al. [60] proposed to estimate the annual soil loss corresponding to a return period *T* for a bare soil ($C = 1$), $SL_{a,T}$, by the following relationship:

$$SL_{a,T} = R_{a,T}\ K\ L\ S \quad (2)$$

in which $R_{a,T}$ is the annual rainfall erosivity factor having a return period of *T* years. Introducing into Eq. (2) the quantile of given return period $x_T = R_{a,T}/R$ of the variable *x*, defined as the ratio between the annual value $R_a$ and *R*, the following Eq. (3) is obtained:

$$SL_{a,T} = x_T\ R\ K\ L\ S \quad (3)$$

Bagarello et al. [53,60,61] carried out the frequency analysis of the normalized variable $x_{SL}$ defined as the ratio between the maximum measured event soil loss for each plot length and recording year and the mean soil loss measured for that event in all plots having the same length. These measurements were collected in the period 1999–2012 in the Sparacia experimental area. The frequency distribution of this normalized variable was well fitted by two Gumbel's probability distributions that were distinguished by the value $x_{SL,To} = 2$. The latter corresponds to a return period *To* of soil loss equal to 25 years. Considering that, in agreement with other literature results, a great amount of yearly soil loss measured at the bare plots of Sparacia was due to the annual maximum value of event soil loss [61], differences between the two temporal scales (event, annual) were considered negligible and the annual tolerable soil loss, *TSL*, was obtained amplifying the mean value of annual maximum event soil loss for given plot length by $x_{SL,To}$.

According to previous results [60], the following value of the tolerable soil loss *TSL*, corresponding to $C = 1$ and $P = 1$, holds:

$$TSL = x_{SL,To}\ R\ K\ L\ S \quad (4)$$

where *RKLS* is the mean annual value of the maximum soil loss (*RKLS*) calculated by USLE/RUSLE. Using of *RKLS* is justified, as suggested above, by negligible differences between the event and annual temporal scales.

Setting the tolerable soil loss (Eq. (4)) equal to the annual soil loss of given return period *T*, calculated by USLE/RUSLE neglecting the effects of control practices, results in:

$$x_{SL,To}\ R\ K\ L\ S = R_{a,T}\ K\ L\ S\ C \tag{5}$$

From Eq. (5) the following relationship can be obtained:

$$x_{SL,To}\ R = R_{a,T}\ C \tag{6}$$

Equation (6) can be rewritten as:

$$C_T = \frac{x_{SL,To}\ R}{R_{a,T}} = \frac{x_{SL,To}}{x_T} \tag{7}$$

in which $C_T$ denotes the specific crop factor $C$ corresponding to a soil loss value equal to the tolerance *TSL*.

*C*-factor considers the combined effect of all interrelated land cover and land management measures [62] and ranges from 0 to 1. *C*-factor values close to zero are characteristics of areas with up to 100% ground cover, whereas values close to one are typical of a bare plot (no vegetation) with till up and down the slope, which is taken as a reference condition ($C = 1$) [6]. The change in *C*-factor from 2010 to 2016 was used as an indicator of the effectiveness of Common Agricultural Policy soil conservation measures in reducing soil erosion in Europe [63].

In agreement with the proposed definition of $C_T$, for a given return period, areas with $C > C_T$ are characterized by soil loss greater than tolerance. These areas should be involved in interventions to reduce the cover and management factor or field length or in the application of support practices.

The proposed approach can be applied in any geographical area if the methodology by Bagarello et al. [53,60,61] holds, $x_{SL,To}$ and $R$ are known, the probability distribution of the annual rainfall erosivity factor $R_a$ is known and its parameters have been estimated.

## 3. Results and discussion

The method of defining the soil loss tolerance condition is based on the proposed comparison between the actual crop factor $C$ and the reference value $C_T$, corresponding to a soil loss value equal to the tolerance *TSL*. This new approach represents an improvement compared to the existing methods for three reasons.

a) it allows us to take into account the actual tolerance of different conditions corresponding to the spatial distributions of *R, K, L, S* factors (Eq. (4)). In other words, the soil loss tolerance condition is not defined using a target value *TLS* [4,49] as this condition is established by matching annual soil loss of given return period and the tolerable soil loss (Eq. (5));
b) it allows us to control if the soil tolerance condition occurs comparing the actual spatial distribution of $C$ with that of $C_T$;
c) it allows designing conservation systems for limiting soil loss using a target value of soil loss corresponding to a specific return period *To* (for the Sicilian region equal to 25 years).

In the following, to demonstrate the applicability of the proposed approach, the case study of Sicilian region is presented. For this region, the statistical analysis [64] of the measured annual rainfall erosivity factor $R_a$, calculated by the procedure of Wischmeier and Smith [42] using the data of 41 recording rain-gauges, was developed and this analysis demonstrated that the Weibull's distribution can be applied [60]. Using Weibull's distribution, the frequency factor $x_T$ is expressed by the following equation [64]:

$$x_T = \frac{R_{a,T}}{R} = \frac{\beta\ (\ln T)^{1/\varepsilon}}{R} \tag{8}$$

in which β and ε are the two parameters of the Weibull's law.

Introducing Eq. (8) into Eq. (7) gives:

$$C_T = \frac{x_{SL,To}}{x_T} = \frac{x_{SL,To}\ \ R}{\beta\ (\ln T)^{1/\varepsilon}} \tag{9}$$

in which β and ε have to be estimated by the following equations:

$$R = \beta\, \Gamma\left(1 + \frac{1}{\varepsilon}\right) \tag{10}$$

$$\sigma(R_a) = \beta\left[\Gamma\left(1 + \frac{2}{\varepsilon}\right) - \Gamma^2\left(1 + \frac{1}{\varepsilon}\right)\right]^{1/2} \tag{11}$$

where Γ is the gamma function and $\sigma(R_a)$ is the standard deviation of the annual rainfall erosivity factor $R_a$.

The use of Eq. (9) requires the knowledge of the target value $x_{SL,To}$, (for example equal to 2 for the Sicilian region), and the estimate of the mean value $R$ and the standard deviation $\sigma(R_a)$.

For the Sicilian region, $R$ can be estimated by the following equation [64]:

$$R = 183.82 + 1.3956\ \left(I_{1,2}\ I_{6,2}\ I_{24,2}\right) \tag{12}$$

in which $R$ is expressed in SI units (MJ mm ha$^{-1}$h$^{-1}$year$^{-1}$) and $I_{1,2}$, $I_{6,2}$, $I_{24,2}$ (mm h$^{-1}$) are the rainfall intensities with 1 h, 6 h and 24 h duration and a return period of two years, respectively. Moreover, $\sigma(R_a)$ can be estimated by the following equation [64]:

$$\sigma(R_a) = -521.63 + 1.38\,R \tag{13}$$

in which $R$ is expressed in SI units.

The analysis developed by Ferro et al. [64] using the $R$ values calculated for 276 Sicilian rain-gauges, allowed for determining the $R$ spatial distribution (isoerodent map) which was characterized by $R$ values falling in the range 500–3000 MJ mm ha$^{-1}$h$^{-1}$year$^{-1}$.

For studying the variability of the reference value $C_T$ with the rainfall erosivity $R$, values included in this range are used. For each fixed $R$ value, the standard deviation $\sigma(R_a)$ is calculated by Eq. (13), while β and ε parameters are estimated by Eqs. (10) and (11) (Fig. 1a and b).

The $C_T$ values, calculated by Eq. (9) with $x_{SL,To} = 2$ and for $T = 100$, 1000, and 10000 years, are plotted in Fig. 2. A sharp difference is detected between $C_T$ values corresponding to $T = 100$ and 1000 years, while a minor difference occurs for $T = 1000$ and 10000 years. For the sake of safety, using $T$ = 1000 years, the following relationship is obtained (Fig. 3):

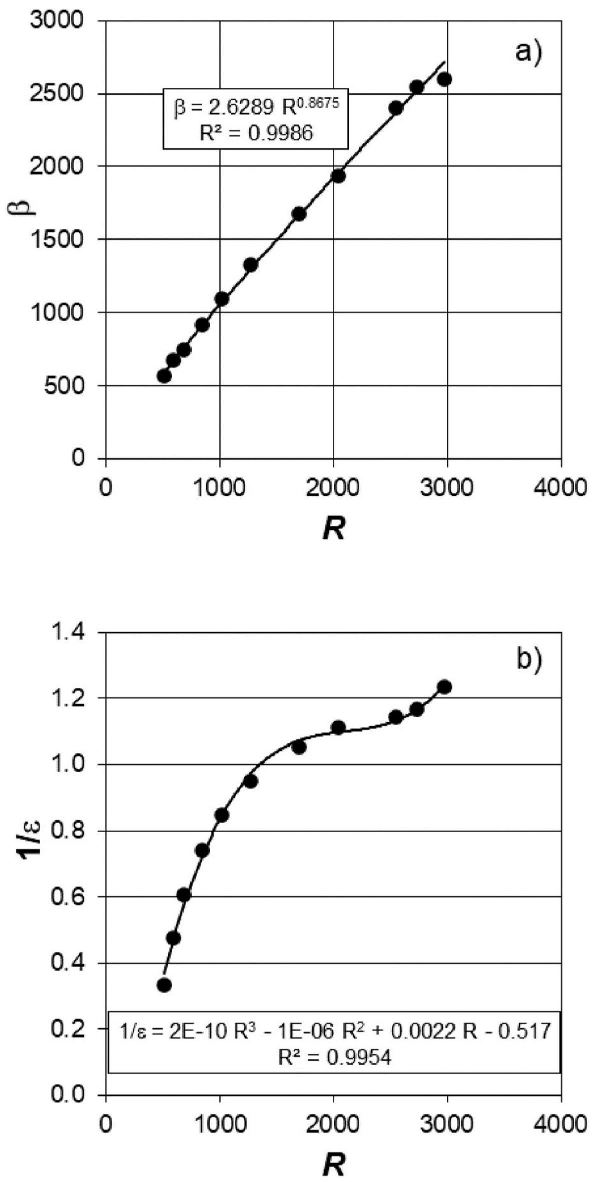


**Fig. 1.** Relationship between $R$ and the parameters β (a) and ε (b) estimated by Eqs. (10) and (11).

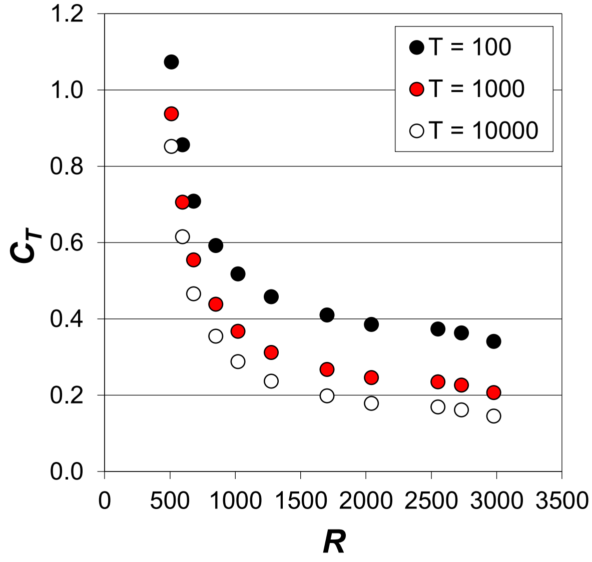


**Fig. 2.** Comparison among the $C_T$ values calculated by Eq. (9) with $x_{SL,To} = 2$ for different return periods.

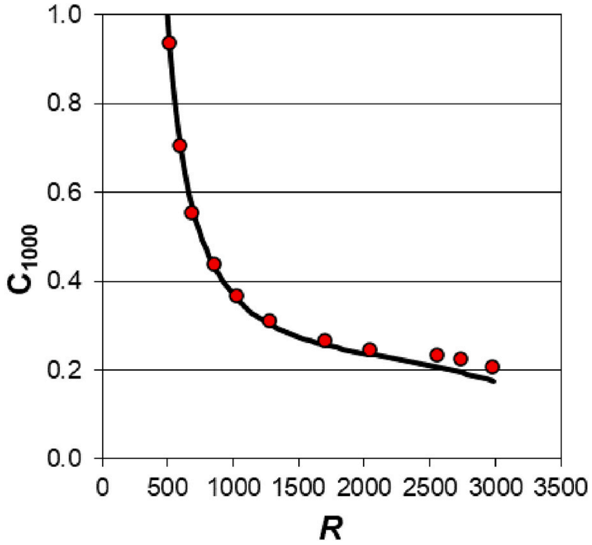


**Fig. 3.** Relationship (Eq. (14)) between $R$ and $C_T$ values, corresponding to a return period $T$ of 1000 years and calculated by Eq. (9) with $x_{SL,To} = 2$.

$$C_{1000} = \frac{1}{\left(5\ 10^{-10}\ R^3 + 3\ 10^{-6}\ R^2 + 0.007\ R - 1.7936\right)} \tag{14}$$

Soil erosion models and risk maps are useful tools that should assist public authorities and political decision makers to establish land use and soil conservation strategies [65]. The isoerodent map, joined with Eqs. (9), (10), (11), (12), and (13)), allows for obtaining the spatial distribution of $C_T$. This last spatial distribution can be intersected with the spatial distribution of $C$, obtained by a land use map, to individuate the areas in which $C > C_T$, i.e., the soil loss tolerance is exceeded. In these areas, land use should be changed to reduce the $C$ factor under the $C_T$ value.

Equation (9) needs the knowledge of both $x_T$ and $x_{SL,To}$. In other words, the probability distribution of $R_a$ has to be established and its parameters must be estimated (i.e., mean and standard deviation of $R_a$ have to be known).

On the other hand, land use could also be a practically unchangeable factor. This is the case, for example, for an area where a given crop (e.g., wheat) is planted every year. Although it is known that this is not the best land use from an economic point of view, the farmer's propensity to change traditional cropping systems could be unlikely. In this case, reducing the $L$ factor by limiting field length could be suggested for practical application.

The changed value, $L_c$, of the slope length factor for a given $C_T$ can be obtained by the following relationship

$$R_{a,T}\ K\ L_c\ S\ C = R_{a,T}\ K\ L\ S\ C_T \tag{15}$$

From Eq. (15) $L_c$ follows as

$$L_C = \left(\frac{C_T}{C}\right) L \tag{16}$$

where $C_T/C < 1$.

Eq. (16) allows establishing that if a farmer wishes to maintain a land use which determines a soil loss greater than the tolerance value, some different soil conservation actions limiting the slope length should be done.

To promote the application of soil conservation measures in the areas characterized by soil loss greater than tolerance, the payment for the provided ecosystem service (PES) could be proportional to the ratio (≤1) between the tolerable *TSL* and the current soil loss of given return period $SL_{a,T}$. Specifically, it could be foreseen the maximum payment for the condition of equality between them (e.g., $C = C_T$) and a proportional reduction to this ratio in the other case (e.g., $C > C_T$).

## 4. Conclusions

Although soil conservation strategies adopted by the Common Agricultural Policy, in the period 2000–2010, reduced soil loss by 20% in cultivated areas, the concern regarding soil erosion is drastically increasing for the normalization of extraordinary rainfall events due to climatic change.

In this context, the European Green Deal is a complete strategy having climate and environmental-related challenges and soils, which are a non-renewable resource, have a main role to reach the sustainable development goals expected for 2030.

Since the payment for ecosystem service is a cost associated with a more environmentally friendly land use, the spatial targeting, which is to establish where to pay, is one of the required information.

As soil conservation strategies/works designed by mean annual value of the climatic variable, as the rainfall erosivity factor, can allow for a suitable erosion control only in the years in which small erosive events occur, a new method to define the tolerable soil loss was proposed.

The proposed approach is based on the statistical analysis of the measured annual values of the rainfall erosivity factor and allows determining the cover and management factor $C_T$ for which the tolerable soil loss is equal to the annual soil loss of given return period.

The available literature methods are based on the comparison between the mean annual soil loss of a given area and the stationary soil loss target value *TSL*, i.e., the tolerable condition simply defined using a value that is assumed as representative of the investigated area. The proposed approach is based on the comparison of the actual $C$ factor with the proposed reference value $C_T$ (Eq. (9)), which is a target value characterized by spatial variability and allows to detect areas in which the soil loss tolerance is exceeded ($C > C_T$) requiring soil conservation strategies.

If the actual cover and management factor is greater than $C_T$, interventions to change land use, reduce field length or apply support practices can be carried out.

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