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Effects of ephemeral gully erosion on soil degradation in a cultivated area in Sicily (Italy)

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Abstract

Water erosion is the main cause of soil degradation on cultivated lands under Mediterranean climate. In these conditions, ephemeral gully erosion (EGE) is a major contributor to loss of soil productivity due to the big amounts of soil removed from the most productive top-layer. However, only a few studies on the effects of EGE and artificial controlling measures on soil degradation are available. The objective of this study was to assess the impact of EGE combined with soil infilling by tillage on several physicochemical soil properties related to soil fertility and productivity through the calculation of a soil quality index (SQI) by means of a statistical approach. It was hypothesized that sites affected by this process of erosion and infilling of ephemeral gullies (EGs) exhibit considerable changes in the soil properties compared with locations that do not undergo this process. The study site consisted of 5 fields with contrasting soil properties which have been continuously cultivated with winter wheat. The site, located in the internal area of Sicily (Italy), represented a typical Mediterranean arable land and was severely affected by EGE. A set of soil sampling were collected to investigate the spatial variation of the SQI across each location: 12 sample points in the EG erosion area; 4 samples in the deposition zone; 4 reference points in the area unaffected by EGE. The SQI was estimated by closely monitoring a set of main chemical and physical soil variables which influence soil fertility status: particle size (sand, silt and clay content), bulk density, gravimetric moisture, pH, electrical conductivity, carbon content (inorganic, organic and total), nitrogen content (ammonium, nitrate and total) and available phosphorus. The results showed that channelized erosion posed a threat to soil quality status even at a single cultivated field's level; therefore, the soil's ability to sustain crop production is expected to be compromised in the long run. Reductions of the SQI were observed at the EGs system area and at the deposition area in every EGs. Besides that, the lowest values of SQI were obtained inside the EGs channel and the nearby soil areas, which were generally used to fill those channels. Soil degradation occurred in the areas which were subjected to EGE and infilling process, with key soil properties being clay (CC), sand (SaC), silt (SiC), and total organic carbon (TOC) contents. This approach helps to understand the impacts of EGE and its controlling measures on soil degradation in Mediterranean agricultural fields.

Keywords: ephemeral gully erosion, soil quality, physicochemical soil properties, soil degradation.

1. Introduction

Soil erosion is considered one of the most important processes of land degradation worldwide, and it represents a serious threat to the provision of food supply and security, protection of human health and natural ecosystems, and economic development of countries. Water erosion processes are classified as sheet or interrill erosion, and linear or channelized erosion (rill and gully erosion) (Boardman, 2006). In temperate regions, almost all cases of erosion involve rilling and/or gullying as the dominant process (Auzet et al., 1993; Boardman, 2006; Chaplot et al., 2005). Different gully types have been described in the literature: permanent or classic, bank, and ephemeral gullies (Poesen et al., 2003). Permanent gullies are landforms created through the incision of alluvial or colluvial deposits by overland or subsurface flows (Rustomji, 2006), which generally result from erosion caused by the concentration of surface runoff during or immediately following heavy rains. These gullies are deep enough (usually >0.50 m) to interfere with, and not to be obliterated by, normal tillage operations (Soil Science Society of America, 2001). On the other side, bank gullies develop whenever concentrated flow crosses an earth bank (Poesen et al., 2003). Finally, ephemeral gullies (EGs) are channel incisions larger than rills, but smaller than classical gullies. They can be removed by conventional tillage, but then recreate at the same location as soon as additional runoff events occur (e.g. Capra and Scicolone, 2002; Capra, 2013; Casalí et al., 1999; Foster, 1986). In agricultural lands, ephemeral gully erosion (EGE) not only determines (sometimes dominant) severe soil loss (Auzet et al., 1993; Poesen et al., 2003; Taguas et al., 2012; Wilson et al., 2008), but also contributes to the gradual degradation of soil quality, which results in a decline in the potential productivity of the soil (Chaplot et al., 2005; Liu et al., 2013).

Soil degradation by EGs is a serious and progressive process which is controlled by two main events recurring over time. One is an increased surface runoff following heavy rain with sufficient erosive power to remove large amounts of surface soil material (Nachtergaele et al., 2001). The other is represented by mechanical operations to fill the eroded surface with soil material from adjacent areas. This practice deletes the gully and restores the original swale of the terrain; however, it also exposes deep soil layers to the erosive action of the EG during the next runoff events. In the long term, the cyclical nature of both processes may gradually lead to a thinner soil profile (i.e. loss of fertility) in areas surrounding the EG, and ultimately to a continued increase in the size of the surface degraded by the gully, due to the use of soil material from increasingly remote areas for infilling the channel (Liu et al., 2013; Yan et al., 2010). In addition, the topsoil fertility, where most nutrients concentrate, gradually decreases from distant unaffected areas to the gully channel. Because of its importance, a quantitative assessment of soil degradation is necessary to reflect how the EGE-infilling process affects soil quality, and therefore, the sustainability of croplands (Doran and Parkin, 1996). Because soil quality cannot be measured directly, this attribute is usually determined by measuring several soil properties (physical, chemical and/or biological), termed indicators; and by trying to set out thresholds for these indicators (Paz-Ferreiro and Fu, 2016; Xu et al., 2006). The literature has reported several studies that were conducted in order to examine type, number, accuracy and thresholds of different soil quality indicators in a wide range of scenarios affected by soil degradation (e.g. scale, land use, conservation practices, etc.) (e.g. Brunner et al., 2008; Douglas et al., 2003; Jackson et al., 2003; Li et al., 2004; Mandal et al., 2008; Tesfahunegn, 2013). These studies concluded that soil quality degradation on agricultural environments affected by soil erosion can be mainly assessed through physical and chemical indicators (Bone et al., 2014; Pulido Moncada et al., 2013; Paz-Ferreiro and Fu, 2016).

However, the scarcity of research on in-situ effects of EGE on soil quality has revealed that there is not a consensus on whether the annual infilling of EGs exacerbates or mitigates soil degradation in the long term, nor on what soil physicochemical properties are more negatively affected and, in consequence, appear as key factors in understanding this degradation process (Xu et al., 2016). For example, Liu et al. (2013) showed that, in the Black Soil Region in China, infilling EGs with soil from surrounding areas resulted in a 2% reduction of crop productivity for every 1 cm of soil removed in these areas. Tang et al. (2013), in the same area of study, concluded that the cyclical process of erosion and infilling of (ephemeral) gullies caused soil degradation through a reduction in the nutrient contents (e.g. organic matter, total and available nitrogen, etc.). Conversely, Xu et al. (2016) showed the primary role of EGE as main drivers of soil physical degradation (e.g. silt, aggregate stability, etc.) by comparing soil samples from different EGs depth profiles with samples from unaffected areas in the central region of the Loess Plateau in China.

In general, there is currently no standard or convention for the assessment of soil quality (Bone et al., 2014) and, in particular, there is no clear information on what main soil indicators should be monitored over time to effectively assess the effects of both EGE and refilling tillage practice on soil degradation (i.e. studied soil function). Selecting soil properties which may serve as suitable indicators of changes in soil quality in erosion-affected ecosystems may help assess the impact of the EG erosion-elimination process on land degradation in quantitative terms. In order to serve as good indicators, selected soil properties should be sensitive, easy to measure (in field and laboratory), verifiable and related to the evaluated soil function (Erkossa et al., 2007).The information provided by indicators can be integrated into a soil quality index (SQI) through a flexible model (Mandal et al., 2008), capable of explaining the status of soil degradation in a specific region and for a determined management goal; according to a minimum data set (MDS) of indicators using different soil measurements (Diack and Stott, 2001; Mukherjee and Lal, 2014). SQI is a sensitive indicator for perceiving the evolution of soil health and quality as conditioned by external agents such as soil (ephemeral) erosion or tillage practice (Xu et al., 2006). Furthermore, spatial variability of these indicators –and therefore the values of SQI– in nearby areas to the gully channel can show the real extent of the negative effect of the above-mentioned erosion-removal process when compared with undisturbed areas (i.e. areas not subject to erosion and infilling process) in the same fields.

From the authors' knowledge, the effects of erosion and infilling of EGs on the physicochemical soil quality and its spatial variation in relation to the area of influence of the erosive channel, or to the areas commonly used to fill it, haven't been evaluated in Mediterranean agricultural environments. The importance of Sicily in southern Italy as one of the most important grain areas under Mediterranean climatic conditions has been reported in a large number of works (e.g. Amato et al., 2013; Ruisi et al., 2014). More specifically, in the central part of Sicily, the process of EGE and subsequent removal by conventional tillage are frequent to occur in agricultural landscapes with steep slopes during the rainy season (e.g. Capra et al., 2012; Capra and La Spada, 2015). The process may constitute a severe threat to the maintenance of the soil fertility status and the protection of soil as a finite environmental resource. Needless to say, in these highly vulnerable croplands a comprehensive set of physical and chemical soil variables can help assess the soil fertility status and, in a dynamic perspective, provide an estimate of changes in soil quality in response to EG erosion. As far as they are responsive, reliable, representative, and easy to measure and interpret, soil attributes are widely used in soil survey programs as well as in studies monitoring changes in the soil fertility/quality status (Doran and Parkin, 1996; Burns et al., 2006). Since many of these soil physical (e.g texture, bulk density) and chemical (pH, electrical conductivity, total organic C, total N, inorganic N-forms, available-P, carbonate content) properties have recently been used to monitor the soil degradation process in large EG-prone areas (Tang et al., 2013; Xu et al., 2016), we focused on these so as to propose a soil quality index for quantitative assessments in five catchments representative of Mediterranean arable lands located in Southern Italy and affected by the combined processes of EG erosion and lateral infilling practice. Specific aims of this study were therefore: (1) to identify what physical and chemical properties primarily linked to nutrient dynamics could be efficiently used as basic attributes in the framework for evaluating site-specific changes in soil quality; (2) to increase the understanding of the impact of EG erosion combined with lateral infilling practice in soil productivity; and (3) to provide recommendations on more appropriate practices to adopt for EG restoration.

2. Materials and methods

2.1. Study area and ephemeral gullies description

The survey site, located in central Sicily (Figure 1), covers a surface area of almost 45 km^2 and extends at an altitude ranging between 220 and 400 m a.s.l. The soil is classified as Vertic Xerocrepts, which is representative of clay soil types (regosols, brown soils and vertisols) located in internal hilly areas of Sicily (Fierotti, 1997), without horizons bounded because of the continuous mixing of layers due to tillage operations, as it is typical for cultivated land. Based on the particle size analysis (see paragraph 2.3) at the study area, the main textural classes are loam and silt loam.

Insert Figure 1 here

The area is mainly cultivated in arable land, with free crop rotation. The main crop is durum wheat sown in October or November (depending on rainfall events) and harvested in June. There are two main tillage operations, the first one is carried out every summer or early autumn with a 0.30-0.35 m-deep cultivator harrow, and the last one consists in a ploughing operation (with a 0.50 m-deep plough) carried out every few years (commonly, a minimum of three years).

The climate is typical Mediterranean with a mean annual rainfall of about 500 mm with a standard deviation of approximately 205 mm. In addition, more than 70% of the rainfall is concentrated in the period from October to May (Capra and La Spada, 2015). During the rainy period, some active EGs usually appear in the studied area (Capra et al., 2009). Before sowing, local farmers adopt artificial techniques to obliterate the EGs by filling them with soil taken from nearby areas to the EG channel, using the ordinary tillage equipment described above. However, EGs frequently reoccur in the same locations during the following rainy season, until they are erased in the July to October period before the next sowing.

The area is also affected by rill-interrill erosion processes. A recent study, conducted in one of the small catchments examined inside the considered area, estimated a soil loss ranging from 18 to 41 tn ha^{-1} year^{-1} (Capra et al., 2012; Porto et al., 2014). These values, especially if associated with those of gully erosion, are believed to be well above the average soil loss tolerated in cropland (Bagarello and Ferro, 2006).

The study site can be considered representative of many cereal areas of South Italy and the Mediterranean areas for soil, cultivation and climatic conditions. In the area described, 5 small catchments (termed EG_1, EG_2, EG_3, EG_4 and EG_5) where active EGs develop in most years along the main swale (Figure 1) have been identified and monitored for EG and soil physicochemical characteristics. Table 2 shows the main characteristics of both the catchments and the EGs. The EG measurement methods are described in Capra and Scicolone (2002) and Capra et al. (2009).

Insert Table 2 here

2.2. Field survey and soil sampling

In our study it was hypothesized that sites with EGE exhibit significant changes in soil physiochemical properties compared with sites without EGE (Xu et al., 2016). In particular, samples of a transect located in the upper area of each of the five EG catchment, not affected by EG erosion, were used as reference points to compare soil properties among the undisturbed area, the EGE and infilling area and the deposition area of the same catchment.

Figure 2 shows the grid-sampling scheme used according to the object of the study. The sampling points were located in 5 transects perpendicular to the main direction of the EGs followed in each location. The transects were in the following positions: one upstream of the basin in an area unaffected by EGE (here named *Tu*), one in the valley-deposit area (*Td*), and three along the EG in the valley (*Tv*), intermediate (*Ti*, at almost 1/3 of the EG channel length) and upper (*Tf*, at almost 2/3 of EG channel length) segments, respectively.

Due to the similarity of the two sides of the EGs, the samples were collected only on the EG hydrological left side. The hypothesis of similarity between the two EG sides is based on: they are submitted to the same crop system, farming practices and soil movement to infill the EG from decades; soil map analysis showed the same parent material; visual analysis showed similar soil indicators (e.g. colour, stoniness, surface cover, surface ponding and crusting); with the exception of the EG5, they have almost the same slope (the EG develops in natural drainage line approximately in the center of the catchment area); their surface area is very small (from 0.33 to 1.85 ha, see Table 2).

Insert Figure 2 here

On each of the 3 transects crossing the EG channel (*Tv*, *Ti* and *Tf*), 4 samples were collected, along lines parallel to the EG in four different positions: one inside the EG channel (sample n. 1), two at properly spaced external points to represent the areas affected by erosion and annual infilling of the EG (samples n. 2 and 3, at almost 1 m and 10 m from the EG running perpendicular, respectively) and one in the area not disturbed by infilling where micro-topography consisted of ridges on the slopes (sample n. 4) (see Figure 2). The 4 samples of the transects *Tu* and *Td* have been collected along the same lines.

Therefore, a total of 100 soil samples (20 for each EG catchment) were taken during a field survey carried out in spring 2014, when the EGs due to the autumn and winter rainfalls were clearly visible and measurable.

In each of the aforementioned sampling points, a composite topsoil sample (three samples collected in an area of almost 1 m^2 of surface) was collected at a depth of 0-5 cm until completion of a sufficient quantity of soil material (ca. 1 kg) for the correct implementation of the following proposed determinations of soil indicators.

Field moist samples were air-dried, sieved at<2 mm particle size and stored at room temperature before chemical characterization. Additionally, 100 undisturbed samples were collected -at the same sampling points- in 100 cm^3 Kopecky rings (5 cm diameter by 5 cm height) to determine-after oven-drying at 105ºC for 24 h- the bulk density (BD) and the gravimetric moisture (GM) of the soil.

2.3. Soil variable measurement

The quantitative assessment of soil quality changes is primarily based on the successful identification of basic soil attributes which best describe any variation. Because of the potentially large amount of data to collect for use in soil quality assessment, minimum data sets have been suggested in literature (see Bone et al., 2014 for a review). The soil attributes selected in the present study (shown in Table 1) for monitoring the soil degradation process due to EGE are consistent with the indicators used according to the minimum data sets criteria (Bone et al., 2014) and with the variables used in similar studies in different environments (Tang et al., 2013; Xu et al., 2016).

Insert Table 1

In particular, the cycles of activation and deletion of EGs has been associated with a selective decrease in the amount of the most fine soil particles (i.e. clays), which results in a soil coarsening (Xu et al., 2016). These particles are involved in the formation of more stable soil aggregates (Boix-Fayos et al., 2001), which improves both soil structure stability and soil water holding. This last attribute and the soil available water capacity are controlled by soil texture and organic matter (Saxton and Rawls, 2006). Hence, particle size analysis was carried out by laser diffraction technology using an ANALYSETTE 22 MicroTec plus (Fritsch, Germany) to obtain the contents of clay (CC), silt (SiC) and sand (SaC) in the soil sample.

Once EGE appears, a reduction in the availability of main nutrients and organic matter in the topsoil were displayed (Tang et al., 2013). This decrease could be exacerbated under successive episodes of filling conducted on EGs when these are formed. In order to assess the latter, the following chemical parameters were determined. The NH_4^+-N (AN) and NO_3^--N (NN) content in 2 M KCl soil extracts was determined colorimetrically by using a Flow Injection Analysis System (FIAS 400 PerkinElmer, Inc., CT, USA) equipped with an AS90 Autosampler (PerkinElmer) and linked to an UV/Vis spectrophotometer Lambda 25 (PerkinElmer). A gas diffusion-mixed indicator method was used to measure ammonium content in the extracts, whereas nitrate content was determined after reduction to nitrite with copperized cadmium and reaction with sulfanilamide and N-(1-naphthyl)-ethylenediamine in HCl solution to form an azo-chromophore. Available phosphorus (AP) content in 0.5 M $NaHCO_3$ (pH 8.5) was determined colorimetrically according to Olsen's method (Horta and Torrent, 2007). Electrical conductivity (EC) and pH were measured, respectively, in a soil/water (1:2) or (1:2.5) (w/v) mixture. The total soil carbon (TC) and nitrogen (TN) were determined by a CN628 LECO (LECO Corporation, USA) automatic elemental analyzer; while the $CaCO_3$ content was determined by the volumetric method of Bernard's calcimeter (Acosta et al., 2010), and the corresponding $CaCO_3$-C (TIC) was then estimated. Then, the total organic carbon (TOC) content was calculated as the difference between TC and TIC. Finally, the relationship value between TOC and TN (TOC/TN) was calculated. This indicator reports the rate at which nitrogen is available to plants, and therefore it can be used as an indicator of the quality of the soil organic matter (Porta et al., 2014).

The effect of the variable BD regarding EGE might be bivalent. On the one hand, elevate BD values have been linked to a higher soil resistance to concentrated flow erosion as a result of a better structural stability caused by the increased in the number of bonds between compacted soil particles (Knapen and Poesen, 2010). However, other studies have reported that erosion increased BD and reduces soil water retention capacity (Frye et al., 1982).

2.4. Determination of soil quality index (SQI)

SQI determination was performed using a statistical model approach (e.g. Andrews et al., 2002a; Li et al., 2013; Mukherjee and Lal, 2014).This type of methodology allows a more objective assessment, identification and score of the soil properties considered in the study thanks to a statistical framework procedure to select the most important indicators of the soil function analyzed, which could avoid any bias or data redundancy which might be generated if a MDS is chosen using subjective techniques, such as the expert's opinion or the review of the literature (Andrews et al., 2002a).Thus, model building was based on the performance of the following three steps: (1) identification and selection of a MDS with the indicators which best represent the soil degradation status; (2) transformation of the indicators value of MDS in non-dimensional values (0-1); and (3) integration of the values of the selected indicators in an index of soil quality (SQI) (Mandal et al., 2008).

The total data set of soil physicochemical properties was reduced to a MDS by applying the following three univariate and multivariate statistical methods with the statistical program R (R Core Team, 2015):

(1) Application of non-parametric statistical Kruskal-Wallis test to identify properties with a significant difference ($p<0.05$) among different perpendicular treatments to the drainage channel in all EGs, and thereby reduce the number of properties candidate to become part of MDS (Andrews and Carroll, 2001).

(2) Implementation of the principal components analysis (PCA) with the set of properties identified as significant after the Kruskal-Wallis test (Andrews et al., 2002b; Mandal et al., 2008). The main function of PCA is to reduce the size of the original set of interrelated variables through the construction of a derived set of uncorrelated variables, called principal components (PCs), and ordered so that the first PC retains most of the explained variance of the entire dataset (Dunteman, 1989; Walpole et al., 2011). The PCs with high

eigenvalues and the variables included in them with a high loading factor represent the maximum variation in the data set information. Thus, according to the Kaiser criterion, only PCs with an eigenvalue higher than 1.0 and accounting for at least 10% of the total variance explained were selected (Kaiser, 1960). In each of the selected PCs, only variables with absolutes values for factor loading within the 10% of the highest value were considered for MDS (Romaniuk et al., 2011).

(3) The Pearson correlation coefficient (multivariate correlation) was carried out when more than one variable was retained under a single PC in order to determine the degree of relationship among variables and to reduce possible redundancy and discard false groups of variables (Andrews et al., 2002a). Therefore, the final MDS was performed by using the following variables for each PC: the variable with the highest factor loading with the factor axis; the variable with the greatest correlation sum, because it presents a greater relationship with the rest of variables and is regarded as the best representative of the group; and the variable(s) with the lowest correlation sums (non-correlated), as they show a relative independence with the group.

After setting the MDS, each selected indicator was converted into numerical values (range 0-1) using the linear scoring functions described in Liebig et al. (2001): less is better, more is better, and optimum. The optimum function identified those indicators which have positive influence up to a certain threshold level beyond which the influence of these indicators over the soil function analyzed could become negative (Fernandes et al., 2011). For 'less is better' indicators, the lowest observed value in the complete dataset was divided by each observation, so that the lowest value had a score of 1; for 'more is better' indicators, each observation was divided by the highest value of the entire dataset, in such a way that the highest observed value received a score of 1; and 'optimum' indicators were scored as 'more is better' up to a threshold value, and, from that point, these values were then scored as 'less is better'.In our study, the critical values for each soil indicator used by the previously linear scoring methods were fixed according to the range of maximum, minimum and mean values of these indicators in the 5 areas of undisturbed soil (i.e. the *Tu* transects at each EG).

After being transformed in numerical scores, the soil indicators were weighed using the PCA results. Thereafter, the SQI was calculated for each treatment by using Equation 1:

$$SQI = \sum_{i=1}^{n} W_i \cdot S_i \qquad (1)$$

where $\boldsymbol{W}$ is the individual PC weighing factor computed by dividing the percentage of variation of every PC by the total percentage of variation of all PCs with the eigenvalue >1.0; $\boldsymbol{S}$ is the indicator score for each soil property in the MDS ($\boldsymbol{i}$), and $\boldsymbol{n}$ is the number of indicators in the MDS. Higher SQI values were regarded to give the best soil quality, and therefore a lower level of soil degradation caused by the EGE-infilled process. Significant differences between the SQI values in treatments were tested using Tukey's test at $p<0.05$. Figure 3 summarizes the work flow and the methodological steps of the statistical procedure developed.

Insert Figure 3 here

3. Results and discussion

3.1. Analysis of soil properties studied in the five EGs

The overall statistics for the 16 soil physicochemical properties measured on the 5 EGs are shown in Table 1. The lowest variation was observed for the physical soil properties (CC, SaC, SiC and BD), as it might be expected from soils with the same parent material. The largest variability among gullies was detected with respect to carbon content ($CaCO_3$, TC, TIC, and TOC) and EC recorded in the EG_5 as compared to the other soil properties. This finding may be due to the nature of parent material. In other words, EG5 originates on an arable site with abundance of coarse calcareous elements (not shown) and high content of soluble salts as a result of soil forming factors. For the rest of indicators, the variability among the 5 catchments was also low. Therefore, it is possible to consider all investigated plots as representative of the overall state of agricultural soil quality in the study area. Thus, it is feasible to analyze the spatial evolution of soil degradation by the impact of the EGE and its subsequent infilling either at an individual plot or considering all the information provided by the spatial sampling framework conducted on the 5 EGs.

3.2. Selection of indicators for the creation of the Minimum Data Set (MDS)

After the application of the 3 statistical analyses described in the methodology, a MDS was selected based on soil properties which proved to be significantly different among the treatments proposed to evaluate the spatial variability of soil degradation in the 5 catchments affected by EGE and infilling process. pH, CC, SaC, SiC, $CaCO_3$, TIC, TOC and AP showed a significant difference among treatments at $p<0.05$ level (in bold in Table 3); and consequently they were selected for PCA, whereas the other properties were discarded for further analysis.

Insert Table 3 here

The PCA with the remaining 8 variables resulted in 3 PCs with an eigenvalue higher than 1 which accounted for approximately 82% of the total explained variance of the entire data set (Table 4). In the first component (PC_1), TOC had the highest contribution to this component according to its factor loading. However, two other properties ($CaCO_3$ and TIC) were selected, because they presented an absolute value for their factor loadings within a 10% variation of the value of the variable with the largest contribution to the component (i.e. TOC). The second component (PC_2) identified two variables: SaC as the variable with the highest contribution to the construction of the factor, and SiC due to its factor loading being within the range of variation established. In contrast, in the third component (PC_3) only one variable, CC, had a high factor loading.

Insert Table 4 here

The Pearson correlation coefficients, as well as correlation sums, were obtained for each of the properties identified with a significant weight on the first two PCs (Table 5).The properties that presented the highest factor loading with each of the three PCs (TOC, SaC and CC) were retained for the MDS. Although both $CaCO_3$ and TIC had the largest sums of correlation, they were discarded because of being strongly correlated with the TOC parameter (correlation coefficient greater than 0.70 and $p<0.05$) (Romaniuk et al, 2011; Mukherjee and Lal, 2014). SiC was selected for the MDS because it presented the smallest sum of correlation.

Insert Table 5 here

Thus, the final MDS was identified by TOC, CC, SaC and SiC. These properties have been identified as indicators of the impact of the EGE on the degradation of the agricultural soils quality in several studies. Xu et al. (2016) reported the highest sensitivity to erosion presented by soil physical properties, rather than soil nutrients, during the development of EGs on loess soils in China. They concluded that, as the EG cross-sections grew in depth, a coarsening of the textural composition of soils was exhibited due to the selective removal of clay particles by erosion, which is reflected in higher values of erodibility and structural instability of soil aggregates. Following the same line, Tang et al. (2013) related the coarsening of the original soil parent material with an increase in soil degradation resulting from the process of erosion and infilling of EGs. TOC parameter reflects the amount of organic carbon stored in soil organic matter, and thus, its reduction represents a decrease in soil productivity (Fahnestock et al., 1995). Accordingly, Liu et al. (2013) found a reduction in the content of organic matter in the soil by ca. 85% of the area affected by the EGE on soybean crops on loess soils in the Black Soil Region in China; in the same area, Tang et al. (2013) showed that gully erosion and gully filling caused a decrease of organic matter by 0.65 % of the cultivated land. For all these reasons, it was possible to consider these 4 soil properties that formed the MDS as key indicators to assess soil degradation caused by the EGE and infilling.

3.3. Soil quality index

SQI values for each treatment were determined using the Equation 1, after obtaining the ***S*** values by means of linear score functions of each indicator of the MDS. Thus, the physical properties of soil (CC, SaC and SiC) were scored as indicators of 'optimal' type, which were scored as 'more is better' up to a certain value or threshold and were then scored as 'less is better' above that threshold (Xu et al., 2016). The critical values for these indicators were selected based on the mean values of the same obtained on the areas not affected by the EGE at the 5 EGs (i.e. *Tu*, see Table 3). For the TOC indicator, the 'more is better' function was applied (Andrews et al., 2002a), by dividing all observations of each treatment by the maximum value of TOC found in the treatment unaffected by the EGE. The significant impact of the EGE and the infilling process of the channel on the reduction in the SQI values in the 5 EGs analyzed is shown in Figure 4. A reduction in the SQI value was observed as we moved downstream from the unaffected area to the deposition area. The highest value for SQI (0.752) was obtained, as expected, in areas not affected by erosion (*Tu*), whereas in areas affected by both the EGE and its subsequent infilling (*Tf*, *Ti*, *Tv*) the SQI ranged between 0.628 and 0.665 (average of 0.648), which meant an average reduction of 13.81% compared to the unaffected zone. The lowest SQI value was obtained for the EGs deposition areas, with a value of 0.557, representing a reduction of 25.93% compared to *Tu*. Tang et al. (2013) determined that soil degradation was observed both in areas of the gully systems affected by erosion and infilling, as in deposition zones thereof; it was associated with a reduction in the organic matter content (i.e. organic carbon, TOC) and in the percentage of textural particles with respect to areas not affected by both processes. Furthermore, in the same study the authors reported that the higher soil degradation in EG deposition areas was due to soil which originated from the process of erosion and infilling of the gullies that buried the fertile topsoil. The same trend was observed in our study, where a decrease by 14.06% in the SQI values was seen on the deposition areas in contrast to the areas affected by EGs systems.

Además de esto, los tratamientos fueron estadísticamnet significativos entre ellos: describirlo: ver si poner antes o despuésde Tang et al. (2013).

Insert Figure 4 here

Additionally the SQI spatial variation in relation to the distance from the channel of the EGs was analyzed. Theoretically, as the perpendicular distance to the EG increases, the level of soil degradation decreases. This is due to the fact that the soil material used for infilling the EG channel during plowing operations comes from nearby areas to the channel (Liu et al., 2013; Tang et al., 2013). For this reason, the values for the indicators of soil samples located in the *Tu* transect could not be taken into account, since they were not affected by the process of erosion and filling of EGs. Figure 5shows the change in SQI values with their standard deviations in four distinct areas depending on the distance to the channel: A, soil samples collected in the EG channel (Tf_1,Ti_1, Tv_1, Td_1); B, soil samples collected at 1 m from the EG channel (Tf_2,Ti_2, Tv_2, Td_2); C, samples collected 10 m away from the EG channel (Tf_3,Ti_3, Tv_3, Td_3); and D, samples collected at a distance large enough to consider them as not affected by the studied process (Tf_4,Ti_4, Tv_4, Td_4). Liu et al. (2013) showed that, at a distance of 10 m from the gully, the soil was still affected by the negative effects of erosion and its infilling.

Insert Figure5here

With the exception of the EG_2, all EGs followed the same pattern of behavior with respect to the spatial variation of SQI. Thus, the mean lowest values for SQI in the 5 gullies occurred in soil samples collected on the channel bed of the EGs (zone A, SQI = 0.600), gradually increasing its value to the area not affected by erosion and infilling (zone D, SQI = 0.642). Thus, the soil surface where EGs ran was the most degraded by removing a certain depth of soil as a consequence of the erosion process. Xu et al. (2016) concluded that soil degradation increases as the depth of the EG increases. SQI values in B and C zones (0.623 and 0.634 respectively) were very similar to those obtained in the EG channel area. This suggests that, at distances close to the EG, soil degradation is even greater, due to the constant loss of topsoil owing to the process of infilling the EG channel with soil material from nearby landscapes areas. This last point matches with the results obtained by Tang et al. (2013), who reported that gully filling operations in zones close to the gully system derived in an increment of soil degradation, when this last zones were compared with areas in the same field not affected by this measure for controlling (ephemeral) gully erosion.

In the D zone, located on the edges of slopes not affected by the EGE, possible soil losses –and thus quality and productivity– were generated only by sheet, rill or tillage erosion. However, in the specific case of EG_2, a reduction in the value of SQI was appreciated in the D zone with respect to the other zones (see Figure 5). In this last gully, the mean values for the key soil indicators are quite similar in the 4 distinct zones (values not shown). The main difference, and possibly the cause of low value for SQI in the D zone, was the lower TOC value compared with this value in the other zones (ca.

7% of reduction in the TOC). This result differs from those of Zhang et al. (2015), who reported a decreased soil organic content in the first 20 cmof topsoil layer on the slopes and bottom slopes areas when compared with the ridge areas in a small watershed in the Black Soil Region in China. However, Liu et al. (2006) found that an increase of the landscape slope might result in a more pronounced soil erosion which then leads to a TOC decline in the same soil layer from the Dehui County farmlands, black soil of northeastern China. Mean slope in the EG_2 catchment was one of the highest (20%, see Table 1). This last finding could have facilitated both transport and down-slope deposition of sediments and nutrients (TOC) by the runoff water flowing in the gully channel direction (A, B and C zones) from unaffected areas (zone D).

Finally, the soil physicochemical indicators used in the construction of SQI were plotted using a radar diagram, with the aim of identifying patterns of quantitative variation of these indicators according to treatments considered (Figure 6.A) and the distance of soil sampling point from the EG channel (Figure 6.B). The lines crossing the four axes were the treatments (i.e. *Tu*, *Tf*, A, B, etc.), where values further away from the center of the graph were assumed as representatives for better soil quality. Thus, a wider area among the four axes corresponds to a higher value of SQI and, therefore, to a low soil degradation (Mandal et al., 2008). Figure 6.A confirms that soil physical properties that determine the soil texture suffered further degradation as we got closer to deposition areas. The highest value for SaC was observed in the unaffected area (*Tu*), while in the areas under the EGE and infilling processes (*Tf*, *Ti*, *Tv*), the values decreased progressively, reaching minimum values in the deposition area (*Td*). The same behavior was observed for TOC. On the contrary, values of CC and SiC progressively increased from undisturbed (*Tu*) to deposition area (*Td*), where they reached their maximum value. These results are consistent with those obtained by Xu et al. (2016), where the continuous removal of fine soil particles and organic matter adhered thereto was associated with a lower erosion resistance (i.e. lower aggregate stability) and a higher state of soil degradation, both conditioned by the progress of the EGE on loess soil type in China.

The highest percentages of fine particles from all treatments were found in the deposition zone (see Table 3). This result was expected due to the deposition of released soil material in upstream areas of the landscape where the topographical factor was not large enough to generate adequate transport power in the erosive flow (Bull and Kirkby, 2002). However, excessive accumulation of this type of particles is an indicator of soil degradation generated by the effect of erosion and infilling of EGs (Tang et al., 2013). Large amounts of these particles alter the original composition of the topsoil, accentuating processes, such as surface sealing or structural instability of the soil among others, that compromise soil productivity of a particular crop (Arshad and Mermut, 1988).

Insert Figure 6here

Figure 6.B shows the evolution of the above key indicators in relation to the distance from the EG channel. The highest values for the 4 indicators appeared in the most remote areas (D), whereas, as we get closer to the channel, the values for these indicators –and thus for SQI–decreased. However, there are no large differences in the values of the SQI (about 7%) among the most remote areas, theoretically less degraded, and the most degraded areas near the channel bed of the EGs.Although not affected by the processes of the EGE and infilling, these remote areas could have been subjected to other erosion processes. Soil physical degradation, commonly apparent on agricultural slopes, could be due to other forms of water erosion (e.g. sheet or rill erosion) or anthropogenic (tillage) erosion (Porto et al., 2014).Moreover, this result confirms the

decision of not using sampling points in D zones in the 3transects crossing EGs and in their deposition area as reference points for primary soil conditions.

4. Conclusions

This paper investigates the effects of the EGE and the subsequent removal process by infilling the EGs on the degradation of soil quality in slope agricultural areas in the central region of Sicily in Italy. The results indicate a decrease in the SQI as we moved away in the downstream direction of areas unaffected by the process analyzed, resulting in a considerable reduction in both the EGs systems and at the sediment deposition area. In the cases examined, SQI mainly depends on soil physical characteristics (textural particle size –CC, SaC and SiC– and gravel content) and organic matter content (TOC). The largest losses in soil quality, compared to the more remote areas not subject to the analyzed process, were obtained in the EGs channel line, as well as in the area within a 10-meter radius of it. Under the studied conditions, not only does the elimination of (ephemeral) gullies through mobilization of soil material from nearby areas fail to mitigate the progressive degradation caused by the erosion process itself, but it even exacerbates the process, being the most affected areas those closest to the location of the EG, as well as the deposition zone, due to the 'off-site' effects of this erosion phenomenon.

The conservation and protection of these physicochemical properties of the soil against the erosion phenomenon analyzed are vital to sustain soil health, which is bound to provide beneficial effects on crop yields and environmental protection at landscape level. In order to avoid the above-mentioned negative effects, it would be necessary to implement innovative land management measures to control the EGE. To achieve these objectives, we suggest using the rank of SQI values obtained under the studied conditions as a promised monitoring tool for the risk assessment of vulnerability to soil degradation caused by the EGE and filling process at specific agricultural lands quite similar to the ones analyzed in this work.

Despite this, it is necessary to widen the type of soil and the physicochemical properties analyzed to broaden our current knowledge on the response to soil degradation against the EGE and filling process in this region.

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Table 1. Main physicochemical soil properties determined in the five catchments constituting the case study of the Mediterranean arable land area.

Chemical properties	Code	EG_1				EG_2				EG_3				EG_4				EG_5			
		Min.	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**
Ammonia nitrogen (mg kg^{-1})	AN	3.92	7.72	5.66	0.85	4.31	8.45	7.02	1.16	3.69	6.11	4.90	0.70	4.82	9.40	6.92	1.36	5.75	8.69	6.75	0.78
Available phosphorus (mg kg^{-1})	AP	7.18	15.13	9.31	1.65	0.67	31.00	10.20	8.46	5.44	56.50	29.13	14.92	5.29	13.61	8.46	2.49	3.54	22.20	9.22	4.71
Calcium carbonate (g kg^{-1})	$CaCO_3$	49.89	78.86	57.37	7.40	51.83	85.18	63.98	9.20	0.00	7.23	1.92	2.23	40.21	105.10	63.88	19.94	213.39	285.86	248.91	17.00
Electrical conductivity (dS m^{-1})	EC	0.25	3.08	1.58	0.74	0.20	5.05	1.18	1.57	0.21	3.13	1.38	1.06	0.71	4.48	2.35	0.85	0.40	8.83	3.52	3.12
Nitrate nitrogen (mg kg^{-1})	NN	0.31	1.53	0.85	0.37	1.03	40.06	7.32	8.62	0.74	8.96	2.90	1.77	0.25	8.41	1.79	2.01	4.29	0.29	1.72	1.03
pH	pH	7.08	7.91	7.52	0.20	7.42	8.06	7.86	0.16	6.80	7.75	7.24	0.30	7.05	7.63	7.43	0.17	7.25	7.92	7.66	0.19
Total carbon (g kg^{-1})	TC	14.04	19.97	16.79	1.91	16.60	24.07	20.31	2.45	6.18	9.76	8.38	0.92	12.38	23.68	16.88	3.59	44.91	56.66	51.25	3.14
Total inorganic carbon (g kg^{-1})	TIC	5.99	9.46	6.88	0.89	6.22	10.22	7.68	1.10	0.00	0.87	0.23	0.27	4.82	12.61	7.67	2.39	25.61	34.30	29.87	2.04
Total nitrogen (g kg^{-1})	TN	0.63	1.56	0.97	0.19	0.87	1.42	1.14	0.15	0.61	0.89	0.76	0.09	0.49	1.47	0.92	0.18	0.93	1.55	1.23	0.15
Total organic carbon (g kg^{-1})	TOC	7.54	13.01	9.91	1.48	7.59	15.60	12.63	2.57	5.70	9.76	8.15	1.03	6.46	11.78	9.22	1.48	12.74	27.67	21.38	3.92
TOC/TN ratio	TOC/TN	6.91	11.77	8.94	1.36	8.09	13.24	11.05	1.51	8.92	13.73	10.75	1.17	6.16	17.05	10.36	2.52	11.51	22.68	17.39	2.85

Physical properties	Code	EG_1				EG_2				EG_3				EG_4				EG_5			
		Min.	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**	**Min.**	**Max.**	**Mean**	**SD[a]**
Bulk density (g cm^{-3})	BD	0.84	1.39	1.06	0.16	0.97	1.32	1.11	0.10	0.86	1.42	1.14	0.16	0.87	1.22	1.06	0.11	0.86	1.44	1.21	0.17
Gravimetric moisture (%)	GM	17.97	26.12	21.60	1.97	27.31	34.10	29.13	1.43	17.00	24.44	21.52	2.05	17.23	28.59	21.42	3.42	26.10	11.87	18.76	5.17
Clay content (%)	CC	5.10	21.34	13.93	5.24	0.16	19.34	5.77	4.36	1.35	16.78	9.98	5.36	7.65	20.91	13.72	3.13	1.54	17.50	8.88	5.86
Sand content (%)	SaC	3.21	33.48	17.32	8.08	12.75	56.35	33.83	10.96	0.64	33.57	17.53	8.85	11.65	37.11	22.59	6.69	32.97	12.86	20.85	6.14
Silt content (%)	SiC	54.30	88.25	68.75	9.62	42.71	78.83	60.39	8.95	64.37	88.86	72.49	8.39	55.24	69.10	63.69	3.86	78.52	59.91	70.28	5.17

a: SD: standard derivation

Max.: maximum value

Min.: minimum value

Table 2. Main characteristics of the ephemeral gullies and their corresponding catchments.

Ephemeral Gully	EG characteristics								Catchment characteristics		
	Measured cross sections (n)	**Length (m)**	**Min width (m)**	**Max width (m)**	**Mean width (m)**	**Min depth (cm)**	**Max depth (cm)**	**Mean depth (cm)**	**Mean slope (%)**	**Perimeter (m)**	**Area (ha)**
EG_1	15	176	0.70	1.00	0.90	10	51	31	10	597.04	1.78
EG_2	17	121	0.60	1.00	0.80	12	58	35	20	284.90	0.42
EG_3	10	118	0.50	1.90	1.20	12	25	19	15	309.00	0.33
EG_4	12	72	0.85	0.60	0.70	6	20	13	16	373.00	1.13
EG_5	18	70	0.90	1.00	1.00	12	48	30	20	661.00	1.85

Table 3. Mean values at the five EGs studied of the soil physical and chemical properties that were selected after the Kruskal-Wallis univariate test applied among the five transects (i.e. treatments).

Treatment[a]	Chemical properties[b]											Physical properties[b]				
	AN	**AP**	**$CaCO_3$**	**EC**	**NN**	**pH**	**TC**	**TIC**	**TN**	**TOC**	**TOC/TN**	**BD**	**CC**	**GM**	**SaC**	**SiC**
Tu	6.675	15.902	97.706	3.183	3.145	7.377	25.772	11.725	0.960	14.048	15.063	1.095	5.809	22.596	32.495	61.696
Tf	5.781	7.864	84.485	1.863	2.170	7.604	21.944	10.138	0.990	11.806	11.362	1.150	10.749	21.236	22.812	66.439
Ti	6.066	12.070	81.553	1.683	2.504	7.584	22.412	9.786	1.015	12.626	11.657	1.074	12.692	22.551	22.739	64.568
Tv	6.118	13.608	84.049	1.314	4.305	7.630	22.841	10.086	1.051	12.755	11.532	1.095	10.628	22.437	23.246	66.126
Td	6.597	16.886	88.279	1.967	2.455	7.515	23.841	10.594	1.004	13.248	12.542	1.167	12.399	23.606	10.833	76.767
$p<\alpha^c$	0.349	**0.033**	**0.032**	0.563	0.069	**0.047**	0.077	**0.032**	0.207	**0.028**	0.090	0.066	**0.041**	0.110	**0.015**	**0.025**

a: *Tu*= unaffected area; *Tf* = upper area of the EG; *Ti* = intermediate area of the EG; *Tv* = valley area of the EG; *Td* = deposition area.

b: the names and the measure units of the soil properties are displayed in the Table 2.

c: level of significance of Kruskal-Wallis test between treatments in the five EGs studied.Values lower than 0.05 are highlighted in bold.

Table 4. Results of principal component analysis with the soil properties identified after the Kruskal-Wallis test.

Statistics results	**PC_1**	**PC_2**	**PC_3**
Eingenvalue	3.250	2.106	1.193
Percentage of variance	40.625	26.319	14.918
Cumulative percentage	40.625	66.944	81.862
Variable factor loading [a,]			
AP	-0.501	0.304	0.547
$CaCO_3$	0.877	0.260	0.011
CC	-0.278	0.316	-0.840
pH	0.587	-0.274	-0.208
SaC	0.253	-0.922	0.249
SiC	-0.114	0.878	0.262
TIC	0.878	0.260	0.011
TOC	0.930	0.285	0.125

a: underlined factor loadings in each variable are considered highly weighed when within 10% of the variation of the absolute values of the highest factor in each PC.

b: the names and the measure units of the soil properties are displayed in the Table 2.

Table 5. Results from the Pearson's correlation test for the most highly weighed variables with high loading factor under PC_1 and PC_2.

Correlation coefficients	**$CaCO_3$**	**CC**	**SaC**	**SiC**	**TIC**	**TOC**
$CaCO_3$	1.000	-0.146	0.029	0.064	0.980	0.856
SaC	-0.146	1.000	-0.529	-0.037	-0.146	-0.190
SiC	0.029	-0.529	1.000	-0.728	0.029	0.004
CC	0.064	-0.037	-0.728	1.000	0.062	0.121
TIC	0.980	-0.146	0.029	0.062	1.000	0.856
TOC	0.856	-0.190	0.004	0.121	0.856	1.000
Correlation sum	3.075	2.049	2.320	2.013	3.073	3.026
Significance level (p)	**$CaCO_3$**	**CC**	**SaC**	**SiC**	**TIC**	**TOC**
$CaCO_3$	NA	0.402	0.775	0.910	0.000	0.001
CC	0.402	NA	0.173	0.682	0.402	0.365
SaC	0.775	0.173	NA	0.018	0.775	0.827
SiC	0.910	0.682	0.018	NA	0.910	0.817
TIC	0.000	0.402	0.775	0.910	NA	0.001
TOC	0.001	0.365	0.827	0.817	0.001	NA

Figure list and captions

Figure 1. Aerial view of the study area with details of the 5 catchments where the ephemeral gullies (EGs) were monitored.

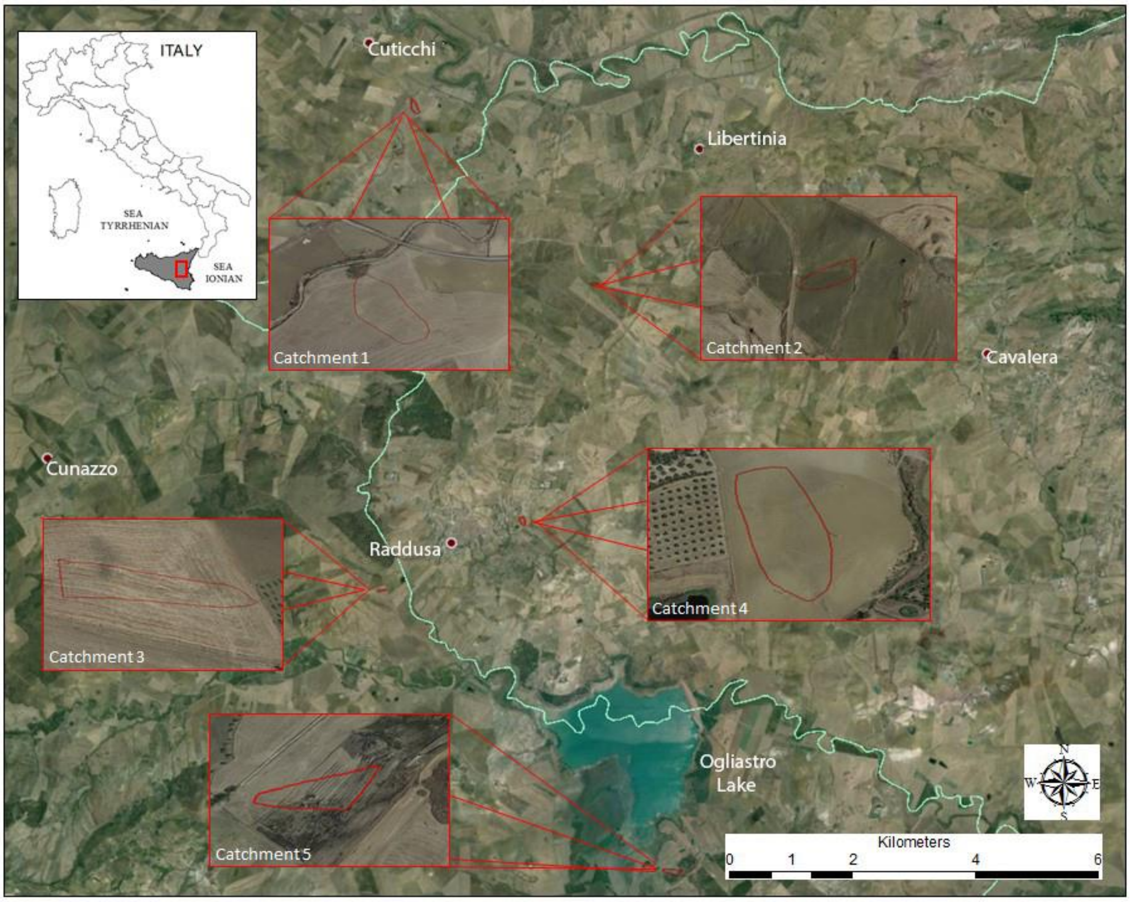
Figure 2. Scheme of the sampling survey followed in every EG. Green stars show unaffected positions where soil reference samples were taken.

Figure 3.Work flow diagram of statistical methodology developed to determinate the SQI at the different points on the catchments affected by the EGE and filling process.

Figure4. Variation of the soil quality index at the different locations in the 5 EGs. Red bars shows the standard deviation at each treatment. Different letters indicate significant differences at $p<0.05$. *Tu* = area unaffected by EGE; *Tf* = area in the upper part of the EG; *Ti* =area in the intermediate part of the EG; *Tv* = downslope area of the EG; *Td* = deposition area of the EG

Figure 5. SQI variation over 4 distinct areas depending on their distance from the EG channel. A= over bed channel; B = 1 m from channel; C = 10 m from channel; y D = distance large enough to be considered as area not affected by the EGE-infilling process.Red bars shows the standard deviation at each area.

Figure 6. Radar plots for SQI and scores in soil properties for each treatments. (A) Five treatments in the downstream direction of the EG; (B) Four treatments based on its distance from the EG channel. *Tu* = area unaffected by EGE; *Tf* = area in the upper part of the EG; *Ti* =area in the intermediate part of the EG; *Tv* = downslope area of the EG; *Td* = deposition area of the EG; A= over bed channel; B = 1 m from channel; C = 10 m from channel; y D = distance large enough to be considered as area not affected by EGE-infilling process.



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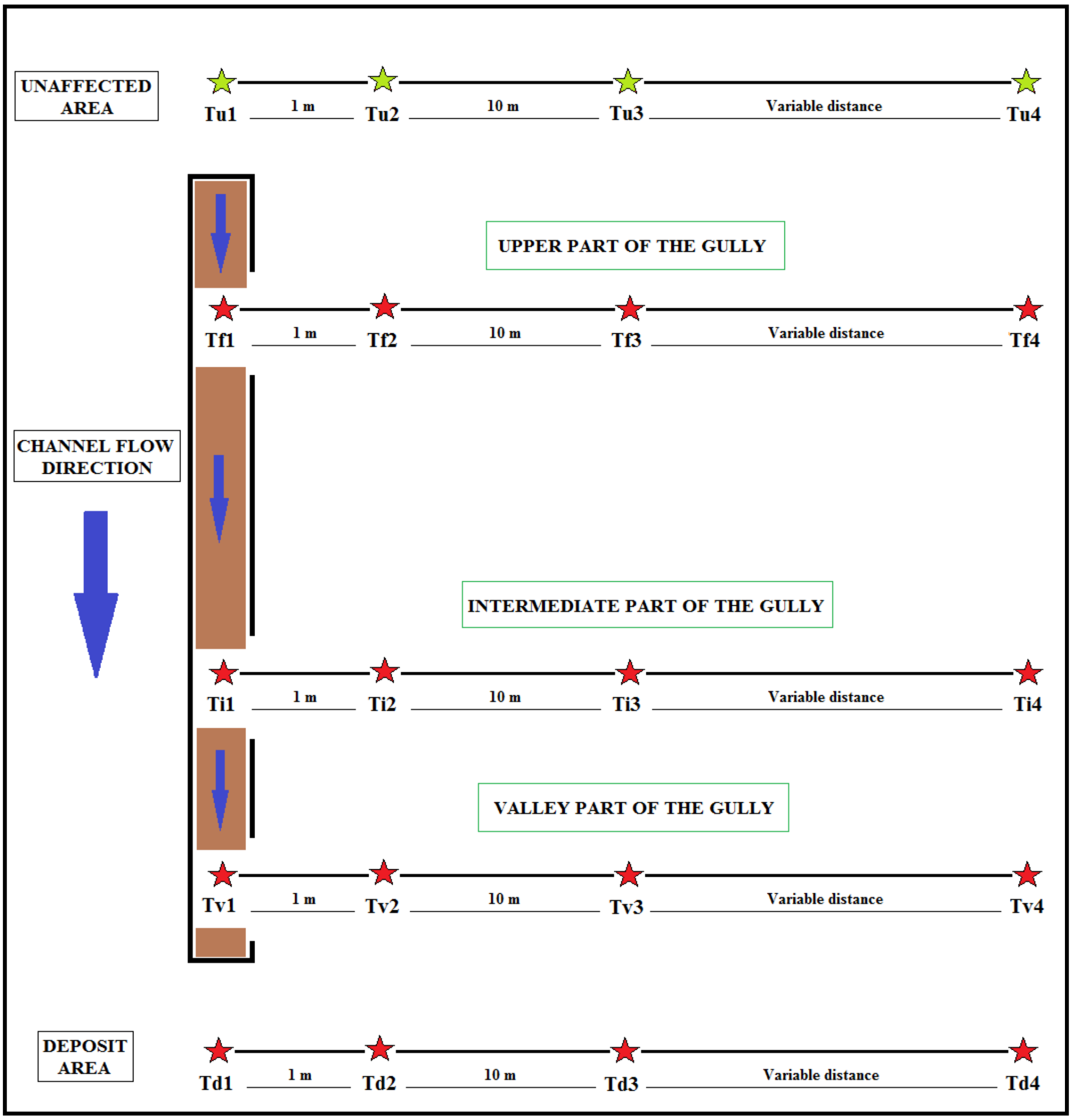

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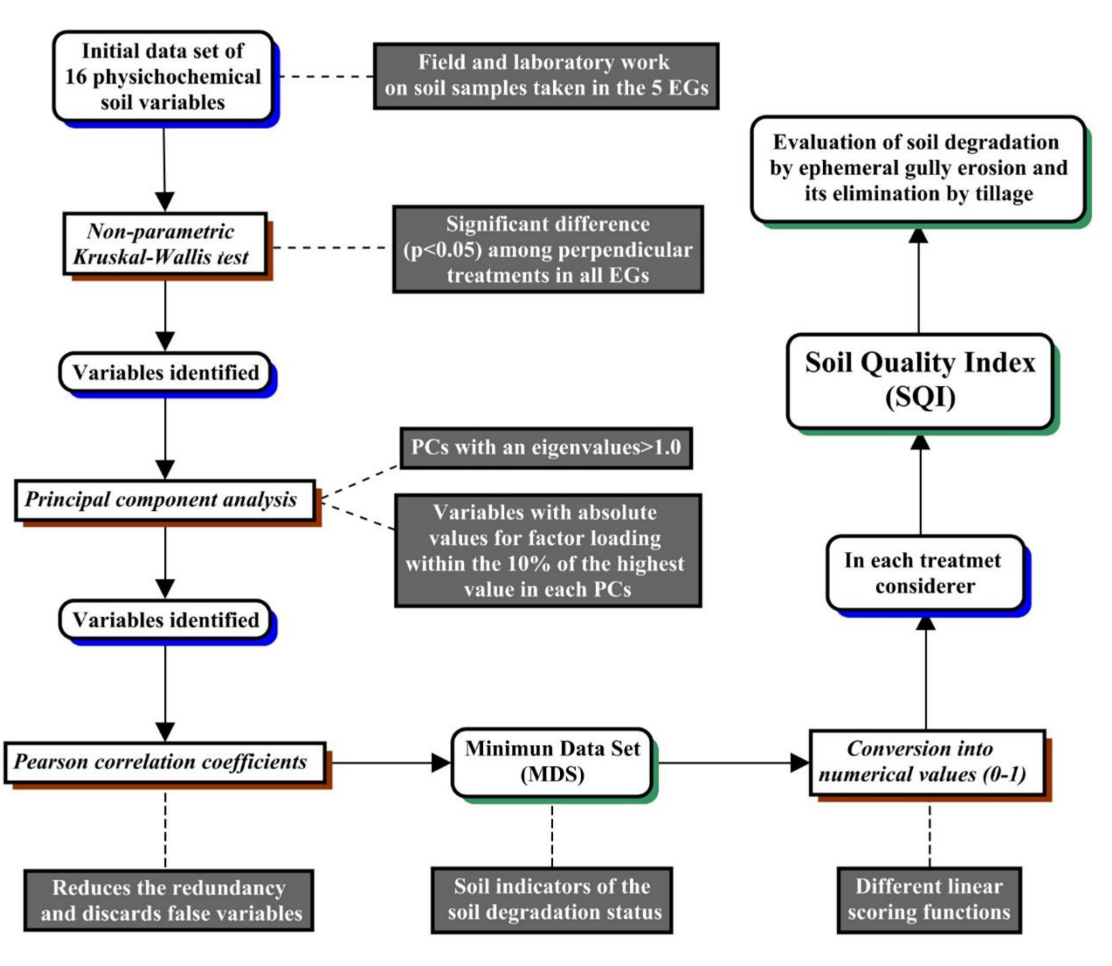

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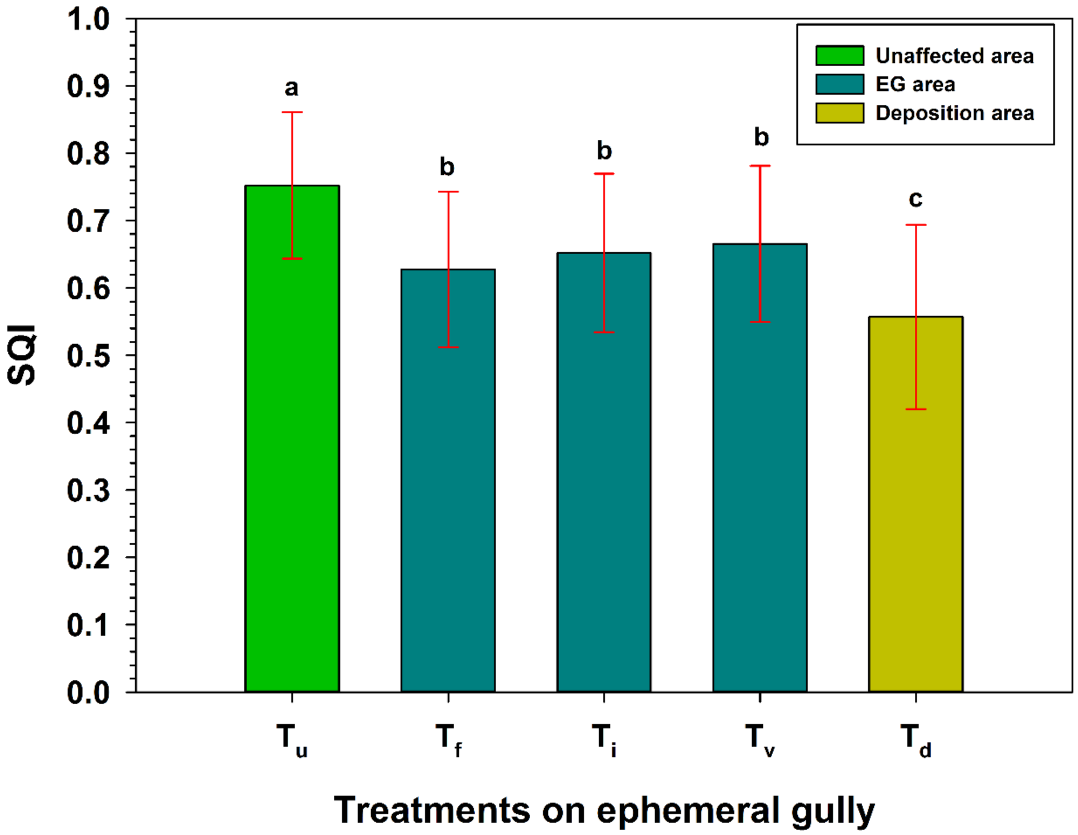

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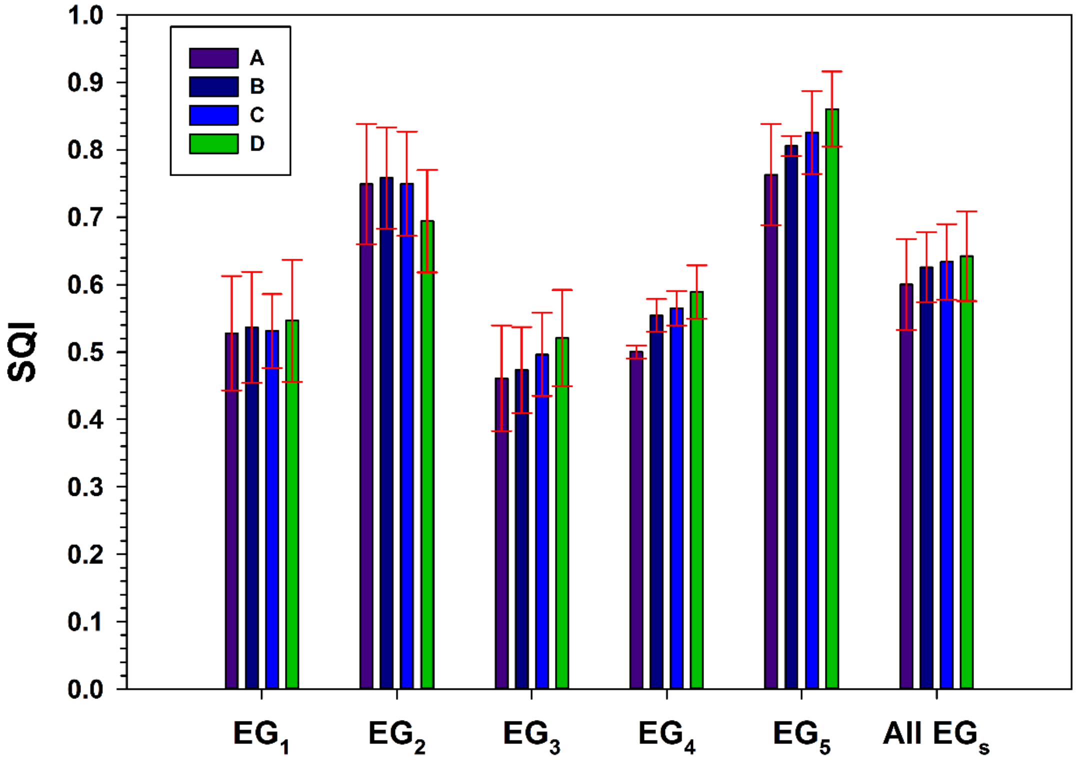

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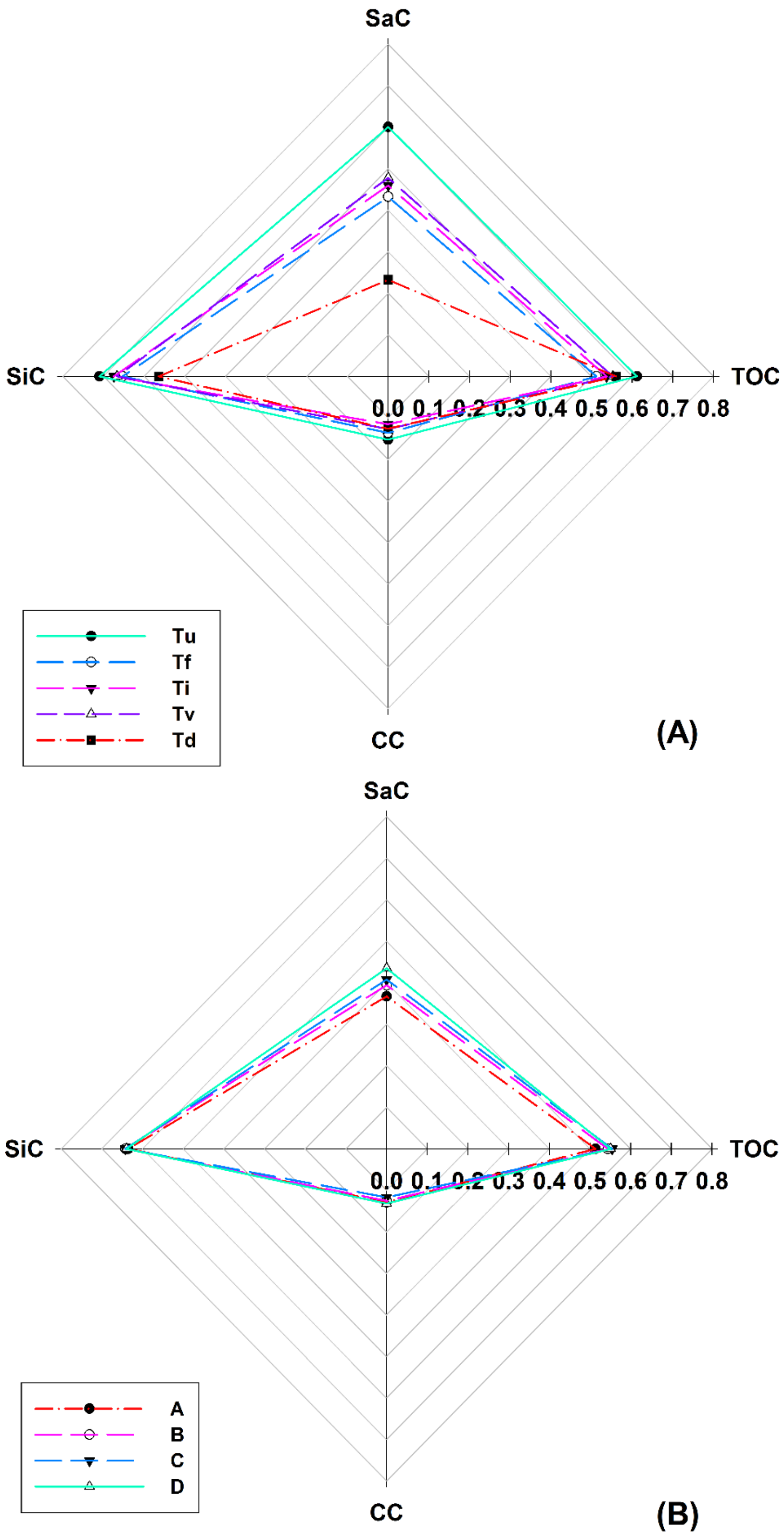

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