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**Article**

# Combining Improved Stock Unearthing Method and ancillary measurements to assess catch crops impacts on soil mobilisation in vineyards

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With 6 figures and 3 tables

**Abstract:** Many aspects regarding the reduction of soil erosion and the effectiveness of nature-based solutions, such as catch crops and their spatial distribution, still remain unknown. To address these questions, in this study, we utilized a combination of the Improved Stock Unearthing Method (ISUM), surveys of biomass and vine vigor, and soil profile characterization in a Mediterranean vineyard located in the unexplored viticultural region of Valle de Lecrín (Granada, Spain). Our findings revealed that the use of catch crops after cutting the vines did not lead to significant changes in soil properties along the profile, including organic matter, aggregate stability, and nutrient content, but there were positive results in reducing soil surface lowering in specific areas. These positive outcomes also correlated with the highest levels of vine vigor, measured by assessing the vine's perimeter at three different heights. ISUM, utilizing the graft union as a passive bioindicator to assess surface lowering predominantly caused by soil erosion rates and surface changes, showed a sedimentation rate of 17.88 t $ha^{-1}yr^{-1}$. Under the vine these rates reached a total of 13.73 t $ha^{-1}yr^{-1}$ and along the rest of the inter-row area much lower values (4.16 t $ha^{-1}yr^{-1}$). We identified areas that are at risk along the inter-rows, assessed the effectiveness of erosion control measures (how much and where should be used), and gave some suggestions to take steps forwards to protect soil health and productivity.

**Keywords:** Improved Stock Unearthing Method, soil erosion, vineyard management, land degradation


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# 1 Introduction

Human activities are exerting significant modifications on natural ecosystems, with soils being among the most adversely affected components (Eekhout & de Vente 2022; Kraamwinkel et al. 2021). Particularly, these actions have profound implications on the final quality of the food and fibers produced, subsequently impacting on human and animal health (Gomiero 2016; Oliver & Gregory 2015). International organizations, institutions and research/technical centres are actively working to identify effective measures, including nature-based solutions (Cohen-Shacham et al. 2016; Keesstra et al. 2018a), and policies aimed at achieving land degradation neutrality (Albaladejo et al. 2021; Baumber et al. 2019; Zaldo-Aubanell et al. 2021). Since the last century, several authors have highlighted soil erosion as a key processes intricately associated with the current deterioration of the land surface (Alewell et al. 2015; Bork et al. 2003; Brown 1981).

Vineyards are particularly vulnerable to soil erosion, making them one of the most impacted land uses along the Mediterranean belt (Prosdocimi et al. 2016) and globally (Rodrigo-Comino 2018). Since the initial research works published in Chile and Germany (Merino et al. 1979; Richter 1979), there has been a continuous increase in the number of publications regarding high soil erosion rates in vineyards. Intense tillage and chemical usage (Bagagiolo et al. 2018; Novara et al. 2013), terraces (Pijl et al. 2019), steep slopes (Marques et al. 2020), the age of the plantation or extreme rainfall events (Ramos 2006), vineyards planted on erodible parent material (Martínez-Casasnovas et al. 2009; Quiquerez et al. 2014) and poor soils (Follain et al. 2012; Mirás-Avalos et al. 2020) are the main factors extensively discussed in recent literature.

Most of the conducted studies have utilized time-consuming and expensive methods, focusing on short-term processes. However, there remains a gap in research that can effectively combine different approaches to model soil erosion from the pedon to larger scales after extensive fieldwork campaigns. Recently, authors have explored the use of ISUM (Improved Stock Unearthing Method; Rodrigo-Comino & Cerdà 2018) and demonstrated its potential as a rapid and cost-effective solution for estimating surface lowering of a field over an extended period. The method can complement soil compaction, connectivity processes (Fressard et al. 2022) or factors related to the RUSLE (Revised Soil Loss Equation, Rodrigo-Comino et al. 2020). By employing ISUM alongside these short-term assessments, a more comprehensive understanding of soil erosion can be achieved, covering both long-term trends and immediate influencing factors. This approach opens new possibilities for studying soil erosion dynamics and management strategies on various spatial and temporal scales.

To date, there has been a notable lack of research investigating how soil properties and various types of soil cover (such as catch crops, straw mulches, geotextiles, etc.) in cultivated fields, specifically vineyards, soil erosion impact and soil surface quality (Abdalla et al. 2019; Blanco-Canqui & Ruis 2020; Novara et al. 2021). However, we identified a question that has not been researched to the date: how soil erosion processes in cultivated fields, managed by farmers using soil erosion protection measures such as cover crops, affect the complete soil profile (from the surface to the parent material) and vine vigor.

While the use of covers as nature-based solutions is generally positive, determining the appropriate amount and spatial distribution of these covers is a crucial consideration to optimize the use of time and economic resources. Hence, our work aims to develop a new concept by employing a combination of short and long-term soil erosion assessment methodologies to gauge the effectiveness of reduced tillage and the application and distribution of catch crops after cutting the vine plants. These methodologies encompass: i) assessing surface lowering rates using vine stocks as passive bioindicators of the soil surface level (ISUM); ii) conducting a comprehensive survey of vegetation cover using micro-plots and collecting dry biomass; iii) providing a thorough description of the soil profile, encompassing physical, chemical, and biological characteristics; and iv) measuring three different parts of the plants to assess vine vigor. To achieve these objectives, we conducted a field campaign from the end of 2021 to the beginning of 2022 in a conventional vineyard located in the Granada province, Southern Spain. Remarkably, no studies have ever been conducted on this topic in this specific region, making our research a pioneering effort in understanding the effects of soil erosion and cover crop management on vineyard ecosystems.

# 2 Materials and methods

## 2.1 Study area

The study area is situated in a vineyard owned by Bodegas Calvente, located in Villamena, a municipality of the province of Granada, within the Valle de Lecrín region (UTMx: 444701.7; UTMy: 4093635.3; Zone 30, Northern Hemisphere). The field is 10 years old and spans a length of 1 km (Fig. 1A) with a constant height (Fig. 1B). Based on data from the Padul Meteorological Station (https://www.juntadeandalucia.es/agriculturay-

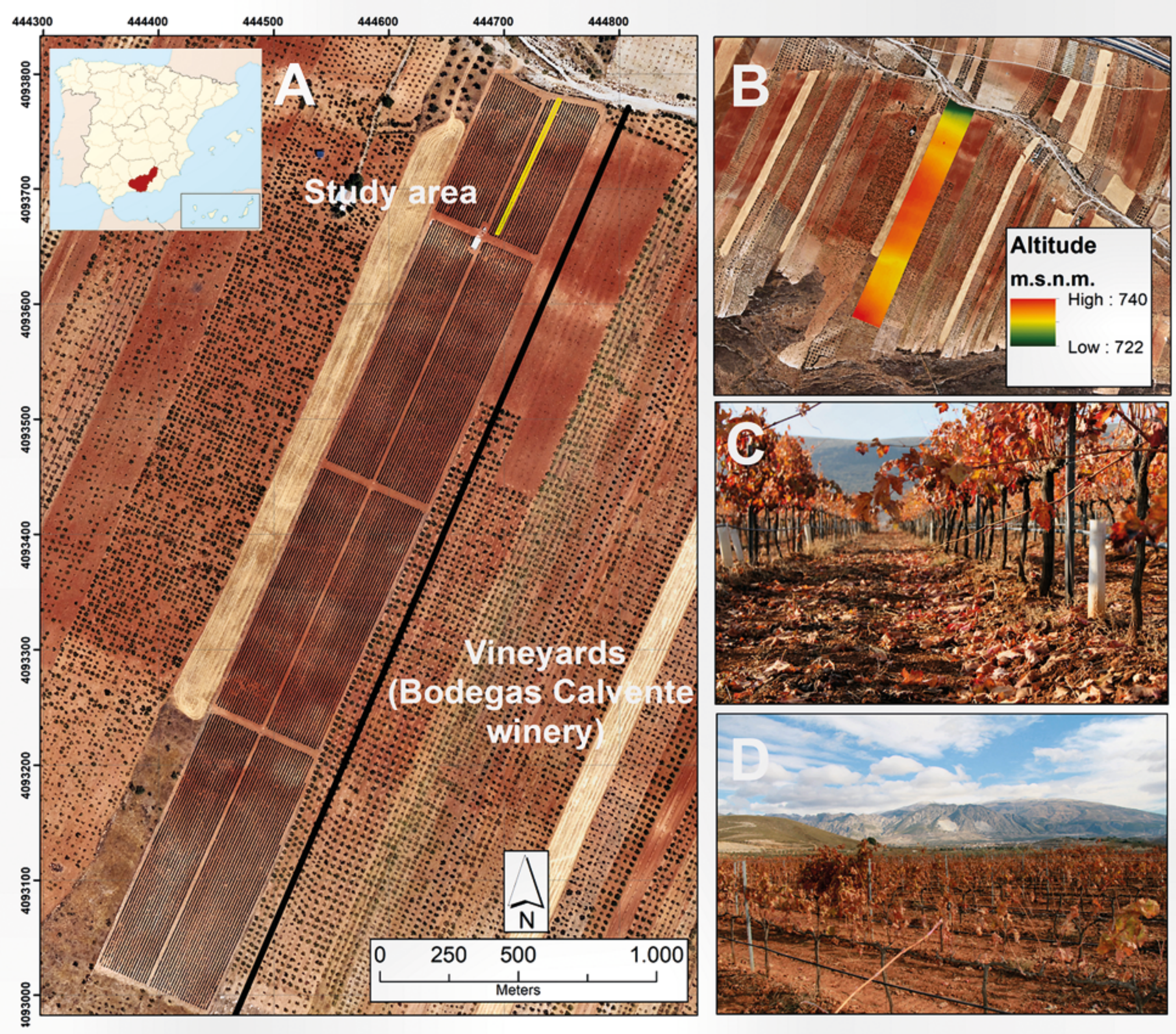


**Fig. 1.** Localisation of the study area.

pesca/ifapa/riaweb/web/estacion/18/10), which is less than 10 km from the study area, the average temperature at the end of February and the beginning of March is 17.2 °C, with average rainfall less than 300 mm and average relative humidity of 48.4%. At the end of spring, the rainfall does not exceed 5 mm, and the average relative humidity is 42.4%.

The parent materials in the area can be classified within the Alpujárride Complex, which includes the mountain ranges of Albuñuelas, Almijara and Guajares, along with the southwestern part of Sierra Nevada. The most recent materials are confined to the Lecrín Valley (Ministerio de Agricultura Pesca y Alimentación 1986). The Mantos Alpujárrides can be categorized into those found to the North of the parallel of Pinos del Valle and those located in the South (IGME 1978). The plot is located in the northern area of Pinos del Valle, occupying an extension between Dúrcal and Jayena (a sector between Tablate and Nigüelas). It is an outcrop with a more restricted extension, where phyllites, limestones and dolomites are not continuous.

According to the data provided by the vine grower, the vineyard produces four grape varieties: Cabernet Sauvignon, Tempranillo, Petit Verdot and Merlot. The crop management carried out on the plot follows conventional practices in all the field with NPK and animal manure, along with dehydrated and pelletized vegetable materials, applied approximately every two or three years. The trade name of the fertilizer is “RIGER” and its composition is 63% organic matter, 3.8% total nitrogen (3.3% corresponds to organic nitrogen), 3% phosphorus ($P_2O_5$), 3% potassium ($K_2O$), 36% organic carbon, 1–5% humic acids, with a C/N ratio between 10 and 12. The heavy metal content is less than the maximum limits of class B (Cu < 350 mg/kg and Zn < 100mg/kg). The vine pruning remains are shredded and added to the ground every year (Fig. 1C and 1D). The irrigation used is dripping fertigation, delivering a volume of 4L per hour in the summer months every 10 days, with each watering lasting for 7 hours. Another fungicide and acaricide called "Belprón" contains 98.5% micronized sulfur (985 g/kg). In May, the stems between 20 and 30 cm long are treated with "Cuprafor 50 Blue," a fungicide, and bactericide consisting of 50% copper oxychloride. The vineyard is planted in a structured pattern with rows spaced 1.09 × 2.3 meters apart. This research was applied in an inter-row area characterized by 123 paired-vines. The hillslope length is 128.6 m. In the complete vineyard plantation, the vines are cultivated alongside the hillslope inclination. The initial plantation height is 4 cm from the current soil surface (Fig. 2A, B, and C), and the vineyard is situated on a gentle slope with an inclination ranging from 10 to 15%, showing an irregular hillslope profile from convex in the foot slope, concave in the back slope, and again concave in the shoulder and summit. The whole hillslope has a total length of more than 1 km.

## 2.2 Soil analysis and statistics

### 2.2.1 Soil laboratory analysis and profile description

Soil samples were randomly chosen from three different inter-rows on February 11, 2022. A soil profile was then opened to a depth of 80 cm using a hoe, and a description was done following IUSS Working Group WRB guidelines (2022). Soil samples were collected with a metal cylinder measuring 4 × 8.4 cm. At each sampling point, three rings were taken from two depths: one from the soil surface or the first centimeters of the profile (0–5 cm, depth A) and the other approximately 5–10 cm from the


**Fig. 2.** ISUM (Improved Stock Unearthing Method), biomass and vine vigor surveys. A, B and C. Example of three recent vine planted considering the 4 cm above the soil surface level; D. Surveying the biomass within the micro-plots; E. Weighting biomass; and, F. Measuring vine vigor at 30 cm height; G. Lifting 30 cm the meter strip to correctly apply ISUM; H and I. Measuring ISUM and workfield notes.

surface (depth B or subsurface). Once extracted from the soil profile, the samples were placed in plastic bags and transported to the laboratory of the Department of Soil Science and Agricultural Chemistry of the Faculty of Sciences of the University of Granada (Spain). The samples were air-dried, which took between 2 to 3 days, then sieved to eliminate the gravel fraction using a 2 mm mesh pore sieve. Texture analysis was performed using the Robinson pipette (Robinson 1922). Carbon and nitrogen content analysis was conducted using a LECO TruSpec. The soil moisture percentage was determined using the Richards membrane method (Richards 1941). Additionally, pH and electrical conductivity analyses were carried out using a digital ph-meter and conductivimeter. Organic carbon content analysis was performed using the Tyurin method (Ball 1964; Nikitin 1999), and bases and cationic exchange capacity were assessed following Khaledian et al. (2017) method. The analysis for calcium carbonate equivalent was performed using the Bernard calcimeter method, and the determination of assimilable phosphorus was carried out following the method described by Olsen et al. (1954). Soil enzymatic activities, including β-Glucosidase, dehydrogenase, and Phosphomonoesterase, were determined following the method of Tabatabai & Bremner (1969). In addition, the induced respiration was measured using the SY-LAB µ-Trac 4200 respirometer. Finally, a bivariate correlation has been carried out to observe the interactions between the different soil properties and components.

## 2.3 Biomass survey and vine vigor

Measuring soil surface characteristics to assess erosion is of paramount for several reasons. Primarily, it aids in quantifying the amount of soil lost from a specific area during a defined period (An & Liu 2017; Arabameri et al. 2018). In this study, to survey the dry biomass weight of catch crops coming from the pruned vines used by farmers to reduce soil erosion and enrich soil nutrients, micro-plots of 0.25 m$^2$ each were established. A total of 75 micro-plots were delimited along twenty-five transversal transects (Fig. 2D). Within each transect, three micro-plots were designated for photography and manual collection of all biomasses within the area, carefully placing the collected biomass in hermetically closed plastic bags. These samples were transported to the laboratory, weighted, air-dried and reweighted to obtain the total wet and dry biomass below the plants, along the tractor pass track, and the middle of the inter-row, where ISUM assessments was conducted (Fig. 2E). The data obtained were then represented using box plots with SPSS 25.0. Additionally, each vine was also surveyed, and measurements were taken at three different parts: immediately above the graft, and at heights of 10 and 30 cm (Fig. 2F). All the data were transformed into vectorial files and georeferenced using control points measured in the field with an Emlid GPS, using ArcMap 10.5 software (ESRI). This georeferencing allows for precise spatial analysis and mapping of the collected data.

## 2.4 ISUM and soil surface lowering rates

The Improved Stock Unearthing Method (ISUM) is a technique employed to estimate soil erosion and sediment mobilization in grafted plants. It involves using the graft union of the plant as a passive bioindicator to assess the soil surface level between the rows (Fig. 2G). After the phylloxera plague, all *Vitis vinifera* were grafted with American stock. Brenot et al. (2006) and Casalí et al. (2009) have shown that the graft union does not grow vertically. By knowing the initial distance of the grafted stock when it was planted, these authors confirmed that it is possible to estimate subsequent changes (such as sedimentation, depletion, compaction, etc.) in the following years if the soil and plant management practices, as well as precipitation trends, are known. Several authors have successfully utilized this method in vineyards and other graft crops, assuming that the initial soil surface level of the planted graft remains constant over the years (Fig. 2A, B, and C) and no horizontal or oblique movements are recorded in each paired plant (Rodrigo-Comino & Cerdà 2018).

The ISUM technique involves conducting cross-sectional surveys for each paired vine, including one measurement every 10 cm (Fig. 2H). By using four-meter strips (two for each vine and one among them, with the last one every 10 cm), we collected a total of 2714 points (118 paired vines × 23 measurements; Fig. 2I) in an area of 1.09 × 128.6 m (0.03 ha). Subsequently, the data were georeferenced and transformed into a shapefile format using ArcGIS 10.5 (ESRI) to generate a digital elevation model of the current soil surface level. We tested a total of eleven interpolation models to obtain the most accurate result, considering the lowest root mean square error (RMSE) and mean error (Table 1).

The Improved Stock Unearthing Method proved to be an effective technique for estimating the soil mobilization rates (Mg ha$^{-1}$ yr$^{-1}$) in vineyards over long-term periods, using the soil loss deposition equation designed by Paroissien et al. (2010). This equation incorporates the age of the vines (y), the volume of soil mobilized (v), the total area (a) and the bulk density (BD). We estimated the bulk density by collecting a total of 24 rings of 100 cm$^3$ along the inter-row area, half below the vines and the rest along the tractor pass tracks (mean 1.37, maximum 1.56 and minimum 1.17 g cm$^{-3}$).

**Table 1.** Interpolation methods used to assess the spatial distribution of soil lowering.

| Interpolation method | Statistical contrasts | |
|---|---|---|
| | Mean error | RMSE |
| Inverse Distance Weighting | −0.11 | 2.31 |
| Global Polynomial Interpolation | −0.00 | 5.31 |
| **Radial Basis Functions*** | **−0.008** | **2.19** |
| Local Polynomial Interpolation | 0.75 | 2.80 |
| Ordinary Kriging | −0.42 | 4.32 |
| Simple Kriging | −0.50 | 2.87 |
| Universal Kriging | −0.42 | 4.32 |
| Areal Interpolation | 0.11 | 2.17 |
| Empirical Bayesian Kriging | 0.058 | 2.076 |
| Kernel Smoothing | 0.06 | 2.09 |
| Diffusion kernel | −0.54 | 4.22 |

# 3 Results and discussion

## 3.1 Soil characterization

### 3.1.1 Soil profile and properties

The soil in the area can be classified as a paleo argic Luvisol, but currently, it is an irragric-calcic Anthrosol (IUSS-WRB 2015; UTMx: 444701.7; UTMy: 4093635.3, Zone 30, Northern Hemisphere) with three horizons (Fig. 3A): a) an Ap horizon (0–10 cm) with abundant loose material, rock fragments (Fig. 3B) and some small and weak aggregates (subangular blocks), which could come from an ancient Bt horizon; b) a Bwk horizon up to 30 cm, heavily modified and deteriorated, where the aggregates have practically the same shape structure, subangular blocks, which have hardly any slats. We hypothesize that there can be found remains of recarbonation coming from old Luvisols, characterized by a process of illuviation of clay (covered by clay) in the gravels (Fig. 3C); c) a Cmk horizon from 30 cm can be found with conglomerates and quartzites included in a carbonate matrix. In most of the area, from 10 to 20 cm, the soil is highly compacted due to the intense tillage, as other authors demonstrated in similarly managed vineyards (Laudicina et al. 2016; Lieskovský & Kenderessy 2014; Napoli et al. 2017).

In Table 2, the soil properties are presented. There were no statistically significant differences ($p < 0.05$) for all textural constituents, indicating that both horizons have a sandy clay loam with more than 30% the clay fraction. These results agree with the fact mentioned earlier regarding the use of tillage, which homogenizes the upper part of the soil surface. The soil water retention capacity at wilting point (−1500 kPa) was found to be 8.6%, and at field capacity (−33 kPa), it was close to 13%. There were no statistically significant differences in water retention capacity between the two depths ($p < 0.05$). Clay textures provide the soil with beneficial chemical properties but often lead to poor physical properties (Fernández-Gálvez et al. 2021; Gabarrón-Galeote et al. 2012). In clayey soils with high water content capacity, the use of machinery can compact the subsurface, leading to soil degradation that negatively affects root development thermal and water conductivity (Al-Shammary et al. 2023). Such practices are known to harm the soil ecosystem, impacting both the soil characteristics and microbial functioning (Hartman et al. 2018; Vink et al. 2021).

Currently, soil management practices such as zero tillage, which includes naturally developed vegetation (Fonteyne et al. 2020), are proposed to protect the soil against splash from precipitation (Abdo 2018; Ruiz-Colmenero et al. 2013). However, some authors are sceptical of this approach, as they have demonstrated that no-tillage does not always prevent soil degradation, particularly concerning soil aggregation and carbon storage, as observed in olive orchards (González-Rosado et al. 2022). In some cases, when no-tillage is combined with herbicide use to eliminate the weeds, soil degradation can worsen.

The homogenization of the soil profile due to the tillage also is also associated with its chemical properties. The pH shows values reaching 7.5 and 7.6 at both depths with no statistically significant differences ($p < 0.05$). The high pH values are directly related to the calcium carbonate content, which is around 40%, giving the soil its basic character. The content of organic matter differs significantly between the surface horizon (1.39%) and the deeper one (1%). A similar trend is observed for total N, P, $K^+$, $Na^+$, $Mg^{2+}$, and $Ca^{2+}$, with higher content in the upper part of the soil profile. There is no correlation between the organic carbon content and the assimilable phosphorus. Therefore, the high values of P could be due to the contribution of fertilizers by the farmer and the mixture with crop residues (Ullah et al. 2023), as previously indicated in the study area description. Likewise, the vineyard soil presents high amounts of clay, positively correlated with exchangeable potassium. The study reveals an inverse relationship between this enzyme and the assimilable phosphorus in plants, suggesting that enzyme activity tends to be inhibited when the phosphorus concentration in the soil is very high. It usually occurs near the rhizosphere and when phosphorus fertilization has been recently applied. Additionally, the enzyme activity is positively related to CEC, $Mg^{2+}$ and $K^+$ and negatively related to pH, similar to findings by Henríquez et al. (2014). The values of this vineyard are

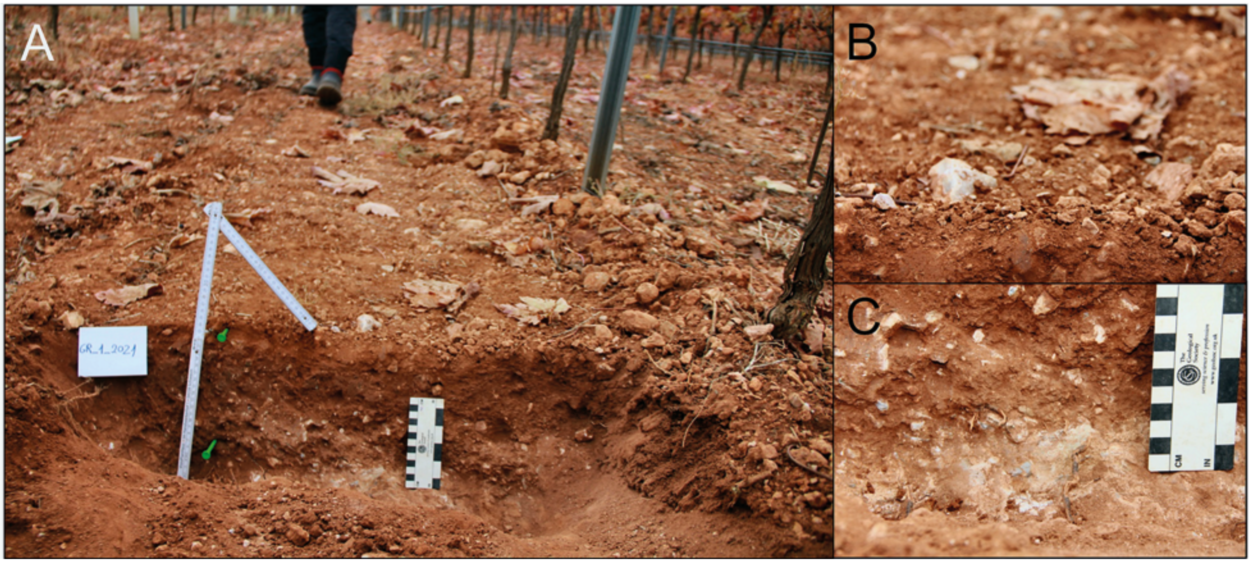


**Fig. 3.** Soil profile details. **A.** General overview of the soil profile; **B.** Photo highlighting the rock fragment cover and embedded ones; **C.** White colour highlighting the carbonate content and the parent material.

very low compared to those of the study, which reported values between 400 and 3000 µg PNP/gh.

Dehydrogenase is considered an index of microbial activity (Kujur et al. 2012). Some authors have reported a positive relationship between dehydrogenase activity and the percentage of organic matter in the soil. This suggests that dehydrogenase serve as an indicator of the metabolic state in which the soil microflora, making it a potential indicator of soil quality (Paz-Ferreiro et al. 2007). However, no correlation is observed between dehydrogenase and organic carbon in this study. The dehydrogenase activity in this vineyard falls within the range values reported in the study conducted by Henríquez et al. (2014). Specifically, the values obtained in this experiment ranged between 0.13 and 4 µg INTFP/gh. However, in comparison with the less degraded soils studied by (Jiménez et al. 2000) are very low, being between 15 and 18 µgINTFP/gh. The values are similar to those of the soil in this study, being approximately 0.5 µgINTFP/gh. Finally, it is worth mentioning that the organic matter content of this vineyard is not very high, therefore, the induced respiration values they present are low compared to those determined, for example, in other vineyards (Tezza et al. 2015).

## 3.2 Biomass survey

The quantification of total biomass per transect along the inter-row area provided valuable information to identify areas particularly vulnerable to erosion, enabling targeted erosion control measures (Hawks et al. 2023; Kort et al. 1998). Our research involved surveying a total of 75 micro-plots (**????Suppl. Material 1?????**) and Fig. 4 illustrates the total weight per plot along the inter-row area. Consistent with previous studies (Bogunović et al. 2016; Capello et al. 2019), our measurements confirmed that tractor tracks, being the most compacted and eroded areas, exhibited the highest weight of biomass (156 g or 624 g $m^{-2}$) among the micro-plots. The weight was measured in transect 45–50, contributing to a total biomass of 1165 g. In the middle of the inter-row, a total of 887 g was reached, with an average of 35.5 g (142 g $m^{-2}$) per microplot. Beneath the vines, a total biomass of 681 g was recorded with average values of 27.7 g (110.8 g $m^{-2}$).

Various studies have demonstrated the benefits of using catch crops to reduce soil erosion and improve soil properties (Constantin et al. 2010; Harasim et al. 2020). We hypothesized that differences might be observed with these applications, confirming the positive benefits of this nature-based solution. However, as we demonstrated with the soil analyses mentioned above, these improvements did not show significant changes from the surface to the lower soil horizons. This is likely because the farmers did not mix the catch crops with lower horizons when they were cut. Moreover, soil properties require an extensive amount of time to show improvement, and the time since the change in soil management may not been sufficient to create a significant impact.

## 3.3 Estimation of soil surface changes and surface lowering rates

Regarding the soil mobilization rates, in Fig. 5A, the soil surface level was mapped using the Radial Basis

**Table 2.** Soil properties of the surveyed vineyard.

| | | Soil texture (%) | | | | SWRC (%) | | pH | EC | OC | Total N | P | $K^+$ | $Na^+$ | $Mg^{2+}$ | $Ca^{2+}$ | CEC | $CaCO_3$ | *Glycosidase* | Dehydrogenase | Phosphomono-esterase | Ind. resp. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Fine silt | Coarse silt | Clay | Wilting point (−1500 kPa) | Field capacity (−33 kPa) | | $dSm^{-1}$ | % | % | mg $kg^{-1}$ | Cmo/kg | | | | | % | µg PNP/gh | | | mg $kg^{-1}$ |
| Ap (old Bt) | Av. | 50.4 | 8.8 | 7.3 | 33.5 | 12.9 | 8.6 | 7.5 | 0.5 | 1.39 | 0.09 | 35.0 | 1.2 | 0.04 | 1.8 | 8.3 | 10.5 | 5.1 | 92.1 | 0.4 | 6.0 | 0.028 |
| | SD | 0.7 | 0.9 | 1.9 | 2.7 | 0.5 | 0.3 | 0.6 | 0.1 | 0.16 | 0.01 | 21.5 | 0.4 | 0.02 | 0.4 | 1.0 | 0.7 | 4.8 | 35.8 | 0.1 | 3.6 | 0.001 |
| Bwk | Av | 49.2 | 10.1 | 10.4 | 30.3 | 13.4 | 8.6 | 7.6 | 0.5 | 1.00 | 0.07 | 14.0 | 0.7 | 0.05 | 1.7 | 8.3 | 10.7 | 5.4 | | | | |
| | SD | 0.73 | 0.92 | 2.1 | 2.3 | 0.5 | 0.4 | 0.6 | 0.2 | 0.17 | 0.02 | 11.4 | 0.3 | 0.04 | 0.5 | 1.3 | 1.3 | 5.4 | | | | |

SWRC: soil water retention capacity; EC: electrical conductivity; OC: organic carbon; CEC: cation exchange capacity; Ind. resp.: inductive respiration; Ap and Bw: soil horizon types; Av.: average; SD: standard deviation.

Functions, which proved to be the best interpolation method among the eleven considered (Table 1). The areas depicted in warm colors indicate soil mobilization, resulting from compaction or depletion. These areas are primarily located in the upper part of the plot (paired vines from 60 to 105 and from 115 to 123), where the soil lowering reaches up to −13 cm. These areas often exhibit soil erosion features, such as ephemeral rills crossing the inter-row area from the left side to the right (Fig. 5B), indicating high connectivity (Cavalli et al. 2013; Crema & Cavalli 2018). High connectivity facilitates water and soil movements.

Immediate downstream of these erosion features, sedimentation occurs. Rodrigo-Comino et al. (2018) have also demonstrated that these soil erosion features can act as barriers, interrupting the connection of soil and water mobilization along an inter-row, a process known as (dis)connectivity (Keesstra et al. 2018b; Wohl et al. 2017). However, to date, there is limited literature considering this process at the pedon scale, which could be helpful in designing suitable nature-based solutions (Keesstra et al. 2018a), such as the use of catch crops or spontaneous vegetation cover. Artificial rills can also be designed to halt soil mobilization across the hillslopes, but high peaks of runoff can generate even more soil erosion problems (Rodrigo-Comino et al. 2017). Most scientific references on the (dis)connectivity process focus on infrastructures, such as dams, dikes and terraces or large amounts of sediments at the catchment scale (Agarwal et al. 2022; Fryirs et al. 2007). Therefore, this would be a new research line to be explored using ISUM and the use of catch crops to avoid the connectivity process among rows and inter-rows.

Estimating the final rates of soil erosion can also help us assess the effectiveness of soil erosion control measures, such as catch crops, and determine how they should be implemented. To achieve this goal, future research should involve monitoring erosion levels before and after the implementation of erosion control measures. This will allow us to determine if the measures are working as intended and adjust them if necessary. In this study case, sedimentation was the predominant process, resulting in a total of 17.88 t $ha^{-1}$ $yr^{-1}$ (Table 3). The results indicate that due to the tractor passes, a total of 13.73 t $ha^{-1}$ $yr^{-1}$ of sediment accumulated under the vines, while the remaining areas which occupy much space, experienced sedimentation at a rate of 4.16 t $ha^{-1}$ $yr^{-1}$. It is worth noting that, after reviewing all the publications related to ISUM, this is the first paper that clearly demonstrate that sedimentation is more prevalent than mobilization in this specific context. Sedimentation occurs at the foot slope, then the upper slope is a source of sediment. Sedimentation is a clear sign of the active soil mobilization along the hillslope. Soil erosion (interrill and ephemeral rills) is an

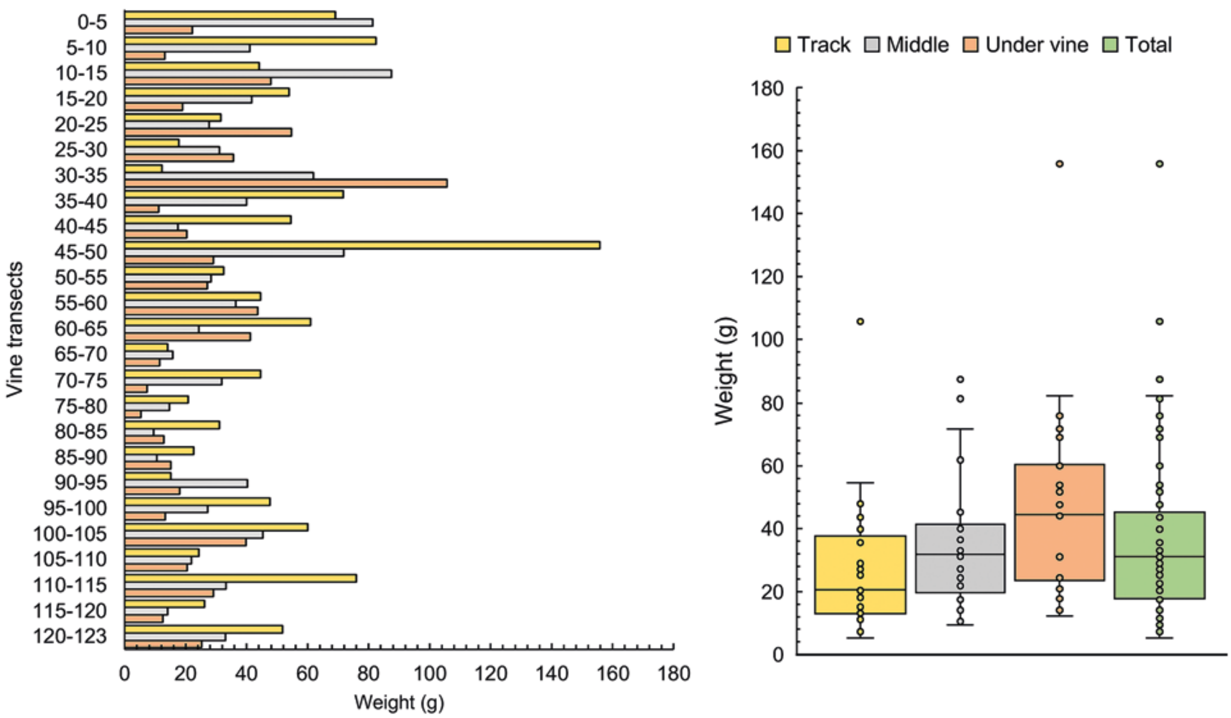


**Fig. 4.** Biomass distribution along the inter-row area.

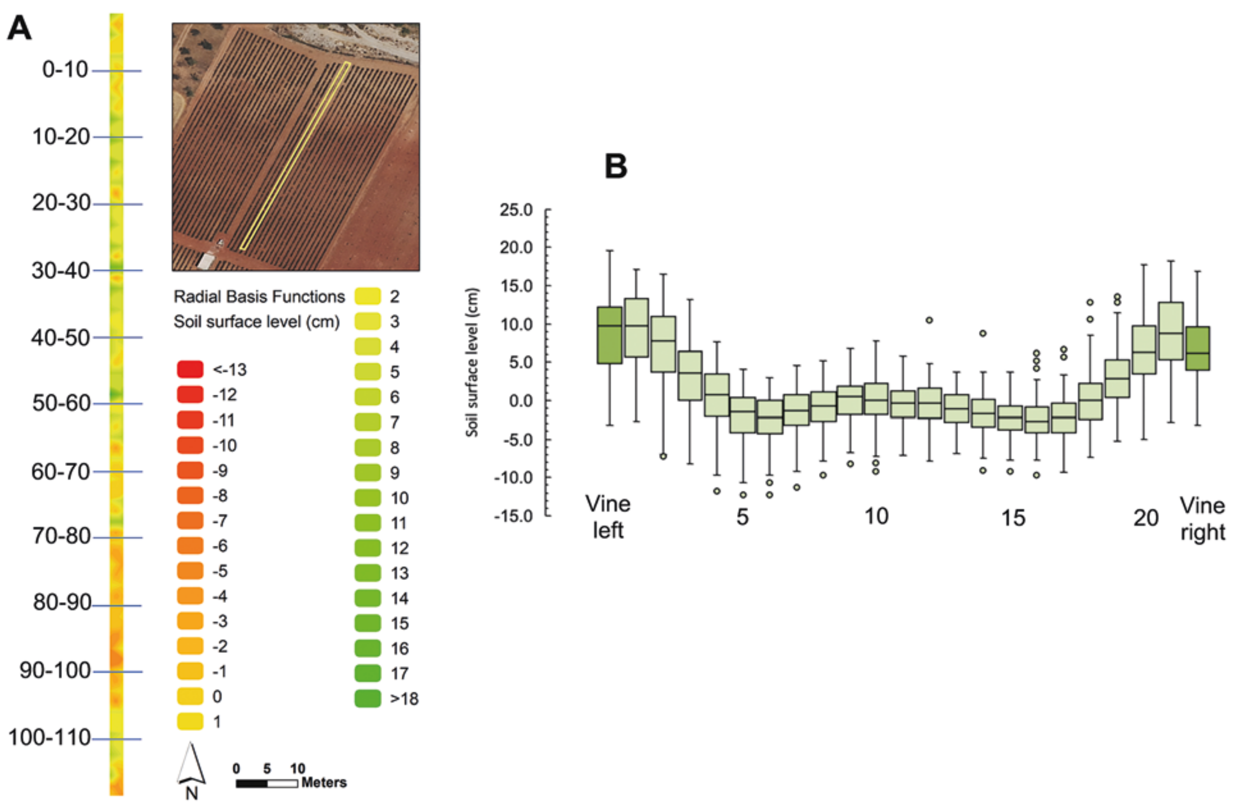


**Fig. 5.** Soil surface level (cm) map **(A)** using ISUM (Improve Stock Unearthing Method) and box plot showing the mean and variation ranges of soil surface level at the cross section level **(B)**.

**Table 3.** Soil mobilisation rates and plot characteristics using ISUM (Improved Stock Unearthing Method).

| Number of paired vines | Total longitude (m) | Plantation framework | Total area ($m^2$) | Total area (ha) | Bulk density ($g\ cm^{-3}$) |
|---|---|---|---|---|---|
| 118 | 128.6 | 2.3 × 1.09 | 295.8 | 0.03 | 1.37 |
| Soil mobilisation | ISUM | Row area | Inter-row | | |
| $m^3$ | 2.32 | 1.78 | 0.54 | | |
| T (in the transect) | 3.17 | 2.44 | 0.74 | | |
| $Mg\ ha\ yr^{-1}$ | 17.88 | 13.73 | 4.16 | | |

intermittent process; therefore, forthcoming investigations should focus on identifying the precise location of the sediment source within the vineyard and understanding the mechanisms by which sediment is redistributed. When selecting the study area, it is essential to consider the entire erosion process, encompassing detachment, transport, and deposition. This comprehensive approach will provide a better understanding of the factors influencing soil erosion in the vineyard and aid in the development of effective erosion management strategies. We acknowledge that the Improved Stock Unearthing Method (ISUM) as a volumetric technique have limitations (bias depending on who measures, time when the measurements are conducted or the consideration of the graft union as a fix bio-marker of soil mobilization), therefore, it would be necessary in the future to validate the results with the use of radionuclides to estimate long-term soil erosion.

## 3.4 Vine vigor survey

In Fig. 6, the distribution of the vine vigor along the surveyed inter-row area is presented. The vine vigor appears to be lower on the left side compared to the right side. On the left side, the vine stocks reach average values of 17.8 cm with maximum values exceeding 34 cm. On the right side, the maximum values are 32.4 cm, and the average is 20.2 cm. The same pattern is observed for measurements taken at 15 and 30 cm from the vine stock. On the left side, they have reach average values of 10.6 and 9.8 cm, respectively, while on the right side, 11.3 and 10.7 cm, respectively. These results align with the previously mentioned patterns, where the paired vines from 60 to 105 and from 115 to 123 experience up to −13 cm of soil lowering. There, the vine vigor is lower at all three measured heights (vine stock, 10 and 30 cm). This observation also corresponds to the dynamic highlighted earlier, where soil erosion features are noted to start from the left and extend towards the right (Fig. 6).

Our results demonstrate that the vine vigor in this row is higher. A remaining research question is whether a more elevated perimeter in three parts of the vines is also associated to higher production and better grape flavours (Novara et al. 2017; Vaudour et al. 2017). This would connect soil erosion processes to soil fertility and grape quality (Ruiz-Colmenero et al. 2011, 2013). In this research, we conclude that soil surface levels, biomass quantity and vine vigor are significantly related.

## 3.5 Discussion and challenges

Nowadays, it is not possible to access real-time data about how much cover crops (%) is up to date used in Europe. However, it is well-known that the use of cover crops in European vineyards was gaining popularity and becoming increasingly recognized for its benefits in sustainable viticulture but also have an important effect in increasing carbon stocks as well. Cover crops are planted between vine rows to improve soil health, prevent erosion, manage weed growth, promote biodiversity, and enhance overall vineyard ecosystem resilience (Garland et al. 2011; Guzmán et al. 2019). It is also obvious that the adoption of cover crops varies across different viticultural regions in Europe, with some areas showing higher implementation rates than others. The percentage of vineyards employing cover crops in Europe depended on the country, region, and individual vineyard management practices. In some progressive grape-growing regions, cover crops were used in a significant portion of vineyards, while in other areas, their use was still more limited. For the most up-to-date information on the status and percentage of cover crop adoption in European vineyards, coming agricultural reports, studies, or reaching out to relevant authorities or viticulture organizations specialised in sustainable practices and viticultural trends in Europe will clarify this practice. In this research, we aimed to emphasize the importance of considering both quantity and spatial distribution in order to reduce soil and water losses in specific parts of the field. This will help the farmers to save their economies but also to be more efficient on time. We demonstrate that this research and using ISUM and the rest of combined surveys allow us to rapidly decide the best amount and place of the catch crops. This research was just applied in an inter-

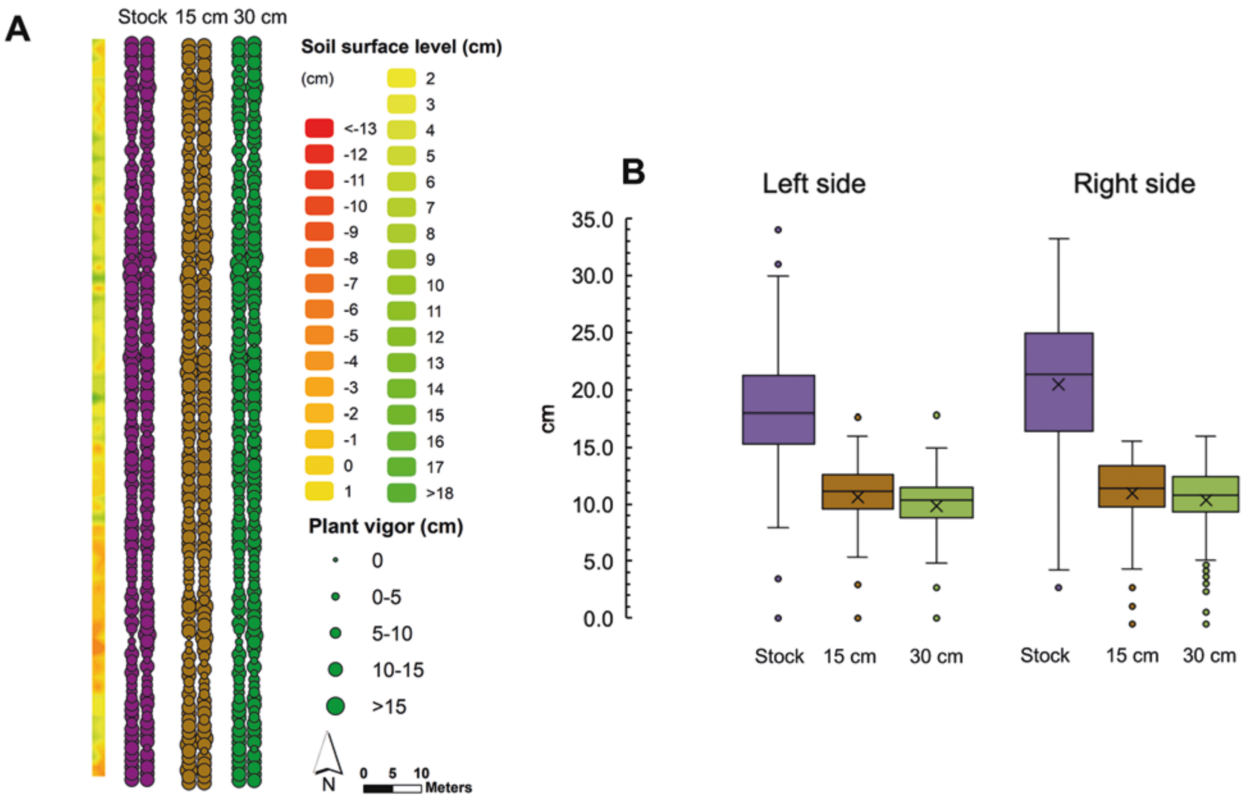


**Fig. 6.** **(A)** Vine vigor and soil surface level (cm) using ISUM and **(B)** box plots showing mean and variation ranges at the stock, 15 and 30 cm vine height.

row area characterized by 123 paired vines, therefore, the next challenge will be to upscale this method to larger areas or in other places within the vineyard selected after detecting using remote sensing or drone flights the most potential vulnerable areas facing constant losses of soil and water.

Overall, we demonstrated that knowledge about soil erosion processes and dynamics is an important tool for improving soil health and preventing environmental and economic damage (Straffelini et al. 2023). It allows us to identify areas that are at risk, assess the effectiveness of erosion control measures, and take steps forwards to improve and protect soil health and productivity. We confirmed that developing new tools and homogenizing methods to measure soil erosion is important for several reasons. First, existing methods may not be accurate or precise enough to provide the information needed to effectively prevent soil erosion. In situ tools like ISUM are designed to provide more accurate and reliable measurements, which can help to identify erosion hotspots and assess the effectiveness of erosion control measures. Secondly, combining existing methods such as ISUM, biomass and vine vigor surveys help to design more cost-effective management strategies and are also easier to use. This can make it easier for farmers and land managers to monitor soil erosion rates and take steps forward for erosion mitigation. Thirdly, new tools can be designed to provide real-time monitoring of erosion rates, which can help to monitor erosion events as they happen and take immediate action to prevent further damage. Finally, this research demonstrated that ISUM, considering the weaknesses associated with the relative position of the graft union and when you conduct the measurements, can be used to measure erosion at a wide range of spatial and temporal scales, from individual events to long-term trends. Overall, we conclude that creating new tools to measure soil erosion is important because it can improve the accuracy, cost-effectiveness, and usability of erosion monitoring to increase public awareness, not only of the policymakers and stakeholders but also rural and urban inhabitants, which are the final consumers of the products produced on erosion prone land. A more comprehensive understanding of the erosion process may help to identify erosion hotspots, assess the effectiveness of erosion control measures, and guide management decisions to protect soil health and productivity.

## 4 Conclusions

Our study revealed an uneven distribution of the soil erosion process within the vineyard under investigation. We observed elevated sedimentation rates in the foot slope area, indicating that the mobilized soil originated from the upper part of the hillslope. The soils in the study area exhibited characteristics influenced by the carbonatation process, with low organic carbon levels and high contents of loose material, potentially leading to reduced aggregate stability. Despite the implementation of catch crops along the soil profile through tillage and soil mobilization processes, we did not observe significant differences in soil physicochemical characteristics. In the eroded sections of the field, there was a noticeable reduction in vine vigor, which may have considerable environmental and economic implications in the long term. Understanding the extent of soil erosion through measurements allows us to grasp the impact on soil fertility, production, and infrastructures. We strongly emphasize that this knowledge empowers land managers and farmers to take proactive measures in mitigating the impacts of land degradation. By extending these findings to other parts of the vine plantations, resources can be optimized, such as reducing the volume and weight of used catch crops, resulting in saved time and efforts. This approach contributes to more sustainable and resilient vineyard management practices for the future.

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