Received: 15 June 2022 | Revised: 7 February 2023 | Accepted: 9 February 2023

DOI: 10.1002/hyp.14829

RESEARCH ARTICLE

WILEY

Estimation of soil mobilization rates by a rainy period and intense tillage practices in vineyards—A case study in the Maule region (Chile)

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Funding information

Universidad de Granada/CBUA; Comunidad de Madrid; Fundación BBVA

Abstract

Winemaking in Chile is a long tradition that is recognized around the world. It is especially important in the Maule region where more than 40% of the total wine in the country is produced. However, there is a lack of studies related to soil erosion in vineyards in Chile, especially considering the extreme rainfall events that occur in the country. This research estimates soil erosion mobilization rates before and after a rainy season between April 2020 and May 2020 using the "improved stock unearthing method" on two inter-row plots in a vineyard located in the Maule region of Chile. This method relies on the graft union as a bioindicator for assessing soil surface-level changes. Maps of the soil surface were obtained to show how soil depletion and accumulation points within the inter-row areas could be detected. It has been estimated that a total soil mobilization of 85.7 and 130 Mg ha yr^{-1} had occurred in the inter-row areas 1 and 2, respectively, since the establishment of the plantation. However, a single rain event mobilized soil at rates of 5.5 and 3.5 Mg ha yr^{-1}, respectively, in the inter-row areas 1 and 2. We have demonstrated that erosive processes present in the study area exceed the rates of soil formation and the tolerable rates of erosion on a global scale. The results allow re-thinking of agricultural practices and management of soil systems to improve the sustainability of conventional Chilean vineyards and their soils.

KEYWORDS

erosion, improved stock unearthing method, sustainable agriculture, vineyards

1 | INTRODUCTION

Globally, about a third of the total arable land has been lost in the last 40 years due to erosion, and at an alarming loss rate of more than 10 million ha per year (FAO, 2015). Many recent investigations estimated that cultivated soils show severe or moderate degradation due to the absence of vegetation cover and the use of herbicides (Cerdà, Daliakopoulos, et al., 2021; Liu et al., 2016), intense tillage practices (Bogunovic et al., 2020; Boulal et al., 2011) and intensification of the productivity with reduced plantation framework (Garnett et al., 2013). Unfortunately, these degradation processes affect billions of people globally (Bork et al., 2003; Pimentel & Burgess, 2013). It is worth mentioning that these impacts affect mainly women, children, and vulnerable socioeconomic groups, especially in rural areas (Bayu, 2020). This is because soil degradation reduces productivity, damages vital ecosystem functions, affects biodiversity and water resources, and increases carbon emissions that augment climate change (Borrelli & Panagos, 2020; Keesstra et al., 2021).

A projection carried out in 1992 by the Land Degradation Assessment in Drylands (LADA) estimated that the global annual cost of soil degradation could be 40 billion US dollars. However, this estimate does not consider the implicit costs such as the need for increased external resources to cultivate degraded lands, the loss of essential ecosystem services for food production, the degraded water quality, or the regulation of the global carbon cycle (http://www.fao.org/land-water/land/land-assessment/es/). In Italian vineyards, some authors presented novel investigations showing the elevated costs in bottles of wines that soil erosion and nutrient losses could cause in the viticulture sector (Galati et al., 2015; Pappalardo et al., 2019). To mitigate the negative impacts of the erosion process, especially, in vineyards, it is necessary to estimate the risk of erosion and to identify the vulnerable areas for adequate territorial planning (Rodrigo-Comino, 2018). However, numerous viticultural areas over the world remain unstudied, for example in China (Yu & Rodrigo-Comino, 2021).

The risk of water erosion in vineyards can be estimated based on the amount and intensity of rainfall, the inherent vulnerability of the soil to erosion, the type of management, and slope characteristics (Biddoccu et al., 2017; Martínez-Casasnovas et al., 2005; Mirás-Avalos et al., 2020). Erosion is influenced by the use of soil or the type of cover, and vineyards present the greatest losses of soil compared to other crops due to the absence of foliage during winter and a low vegetation cover during summer (Pijl, Barneveld, et al., 2019; Prosdocimi et al., 2016). Many vineyards have also exceeded their ecological limits since most occupy places in critical conditions such as steep slopes, shallow and rocky soils, and arid climatic conditions (Diti et al., 2020; Marques et al., 2020; Novák et al., 2014).

In Chile, the first study on erosion in vineyards was carried out by Merino et al. (1979) in the province of Ñuble. There are no other studies in the country that relate land use and soil management to erosive processes. Wine-growing activity in Chile covers 114 448 ha, and there is a concentration in the Maule region (data obtained from the National Commission for Scientific Research and Technology). The soils exhibit an irregular roughness with an elevated rock fragment content and are on slopes greater than 10%. Crop growing is carried out through traditional systems devoid of vegetation cover that promote soil loss due to water erosion. With population growth, erosion rates have doubled in the last 50 years, affecting 60% of the total land (Ellies, 2000). The Natural Resources Research Institute estimated that the total eroded area in Chile covers 34.7 million ha (45.7% of the total area), representing 75% of the high level of erosion (Pino Sanhueza, 2008).

It is well-known that soil erosion depends on the intensity and distribution of precipitation (e.g., Ares et al., 2016; Burbank et al., 2003). In the central and southern parts of Chile, between 5 and 8% of the annual precipitation is characterised by high kinetic energy (Ellies, 2000; Panagos et al., 2017). Regions like the Mediterranean with contrasting seasons present high rates of erosion due to initial rain events following a dry period (López-Bermúdez et al., 1998; Nunes et al., 2008). Nonconservative soil management and nonsustainable irrigation practices, together with the lack of vegetation cover during winter, cause serious erosive impacts, leaving soils saturated during the rainfall period, increasing surface runoff, and generating heavy erosion such as gullies (Estrany et al., 2019; López-Vicente et al., 2013; Poesen, 1981).

The main aim of this research is to assess soil erosion processes in operational conventional viticulture in the Maule region in Chile. Different soil management techniques, such as the use of cover crops or catch crops, could be applied as proposed some decades ago to mitigate soil erosion (Merino et al., 1979). For the case study region, there is a predominance of forestry and livestock, therefore sustainable viticulture is essential to conserve the landscape and biodiversity since a total of 17 784 ha are planted with vineyards (Corporación Nacional Forestal, 1999). To achieve our aim, the so-called "Improved Stocked Unearthing Method" (ISUM) was used to estimate soil mobilization before and after one rainy period, and to assess which parts of the inter-row areas were more affected by soil depletion and accumulation. The method was implemented twice: before the start of the rainy season in March 2020 and after the highest annual precipitation period at the end of May 2020.

2 | DATA AND METHODS

2.1 | Study area

We selected a vineyard (centred on UTM 6045242 N 247728 E) belonging to the Viña Saavedra in the El Morro Melozal sector of the San Javier commune (Maule region, Chile) (Figure 1) for the case study.

The Maule Region experiences winter rains and a prolonged dry season (more than six months) and are classified as a Temperate-Warm (Csb) climate in accordance with the Köppen and Geiger (Köpppen & Geiger, 1954) climatic classification (Peel et al., 2007). Maule has a thermal homogeneity between the averages of the seasons (Corporación Nacional Forestal, 1999). San Javier is dynamic in terms of temperature due to its location, with an average annual temperature of 13°C. The average maximum temperature is around 30°C during both summer and winter, and the average minimum temperature is close to 2°C (Rubel & Kottek, 2010). The dominant rainy periods (78.5% of the annual, range of 800–1000 mm) occur from May to September (INE, 2017).

The study area is located at the intersection of two valleys, two relevant morphostructural domains of quaternary deposits corresponding to fluvial and glacial sediments. They are characterised by soft hills (between 300 and 700 m), units that belong to the Lower Jurassic with fossiliferous marine sediments ((SERNAGEOMIN, 2003)). In the studied area, the average slope is 12.4% (7°) with a maximum of 23% (13°) in the upper half of the inter-row zones and a minimum of 7% (4°) towards the end of both inter-row zones.

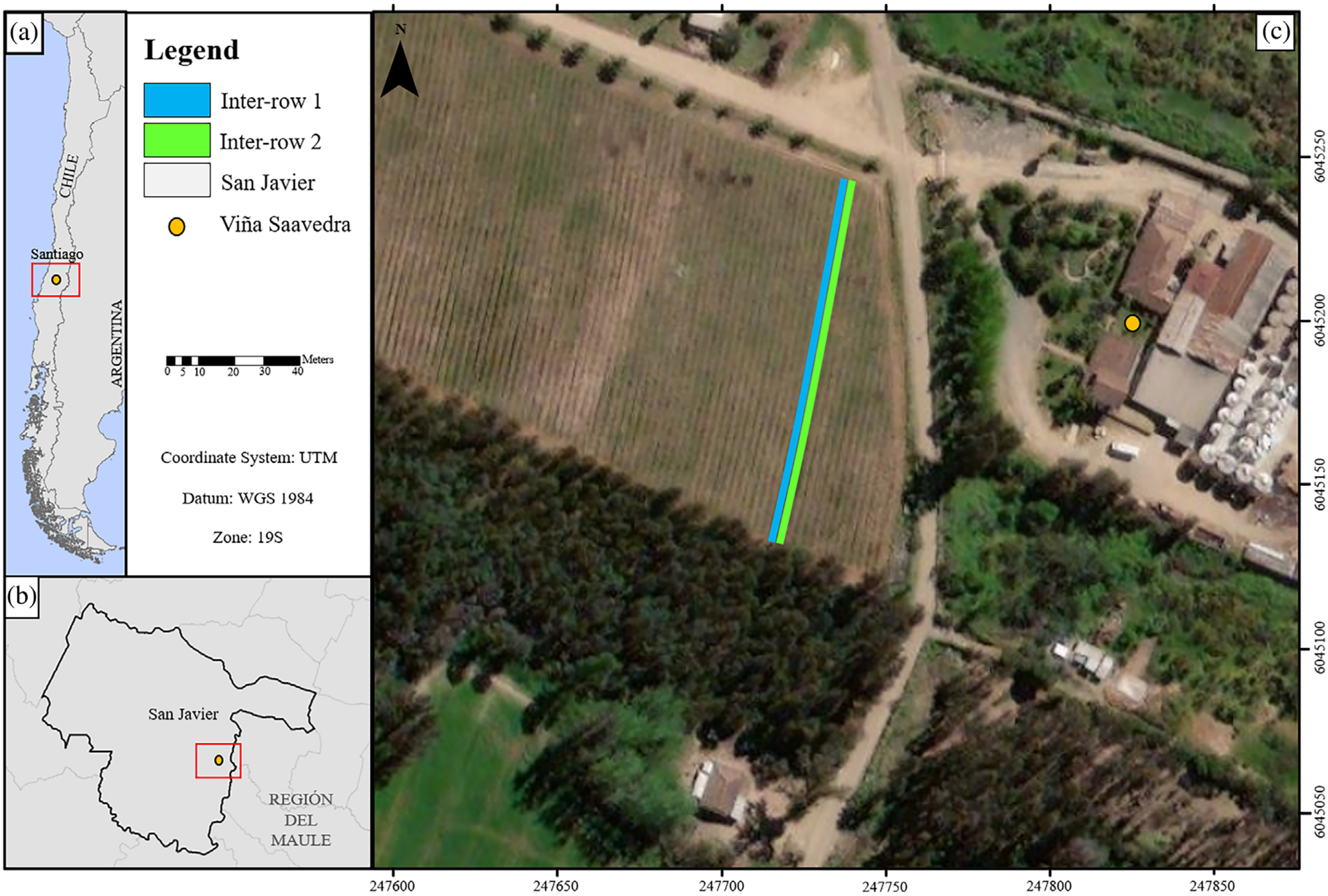

FIGURE 1 Location of the study area: (a) location in Chile; (b) location in the San Javier province; (c) the two inter-row experimental plots sites.

The described morphology, together with the quality of the soils and the availability of irrigation, determine the suitability of the soils for agriculture in the area. The northeastern sector, part of the Maule River basin, is under intensive agriculture. Although nearly 82% of the territory is occupied by large farms (>100 ha), in this area small farms (<20 ha) are predominant. Here different types of crops are included, such as fruit trees, cereals, fodder, and vineyards (Barrios & Le-Bert, 2018). To the west, the land use is rather extensive for meadows, vineyards, and silvicultural activity (Luebert & Pliscoff, 2018) due to the high proportion of silica and quartz, the predominance of shallow soils, low organic matter content, and low moisture retention in soils. All of these factors lead to loss of plant cover and, therefore, soil degradation (Ellies, 2000). In the Central Valley, entisols, alfisols, inceptisols, and vertisols can be found (Soil Survey Staff, 2014). In the alluvial terraces, the thin soils have a coarse texture and the moderately deep soils have a relatively fine texture. The soils are also found on duripan and clay horizons with a loose structure and reduced gravel content, leading to poor drainage. The water table has a maximum height of between 20 and 60 cm (Taucare et al., 2023). The chemical properties of the soil are summarised in Table 1.

The vineyard is located in Garrison n. 1 of the Crucesillas estate. It measures approximately 4 ha and the grape variety corresponds to the Cabernet Sauvignon. There are more than 100 rows of vines oriented from northeast to southwest. Each row has a length of around 107 m, and the inter-vine row distance is 2.5 m. It should be noted that the vineyard is grafted at the surface, which makes it possible to implement the ISUM approach. The management practices include the movement of machinery such as tractors, turbo diffusers, grass cutters, vine shredders, backhoes, and excavators for road repairs, land preparation, and channel cleaning. The machinery passes for a period between 15 days and one month in all the plantations, and about 2 to 3 times per year. The harvest is 80% mechanized with a harvester service between mid-March and late May. Irrigation is 70% by drip. About 300 bovine cattle grazing there serve as weed control. Organic waste from the winemaking process is used as a natural fertilizer, and the chemicals applied are indicated in Table 1.

2.2 | Method

2.2.1 | Improved stock unearthing method

This quantitative and direct method involves taking measurements between the union of the graft and the soil surface (Figure 2). The graft union represents the initial position, in this case at 0 cm from

TABLE 1 Soil chemical properties and chemicals used in the conventional vineyard system in El Morro, Melozal (2020)

Soil chemical properties					
N (mg/kg)	**P (mg/kg)**	**K (mg/Kg)**	**Organic matter (%)**	**pH**	**Electrical conductivity (dS/m)**
5	24	226	2.15	6.01	0.049

Chemicals used		
Product	**Active ingredient**	**Application date**
Basfoliar Zn 55 WP	Zinc	Nov 18–19
Defender Boro	Boron	Nov 18–19
Karathane Gold	Meptyldinocap	Sep 18–19
Superazufre Super S	Sulfur	Nov to Feb
Rufast 75 EW	Acrinathrin	Oct 24–25
Zero 5 EC	Cyhalothrin	Oct, Dec, and Feb

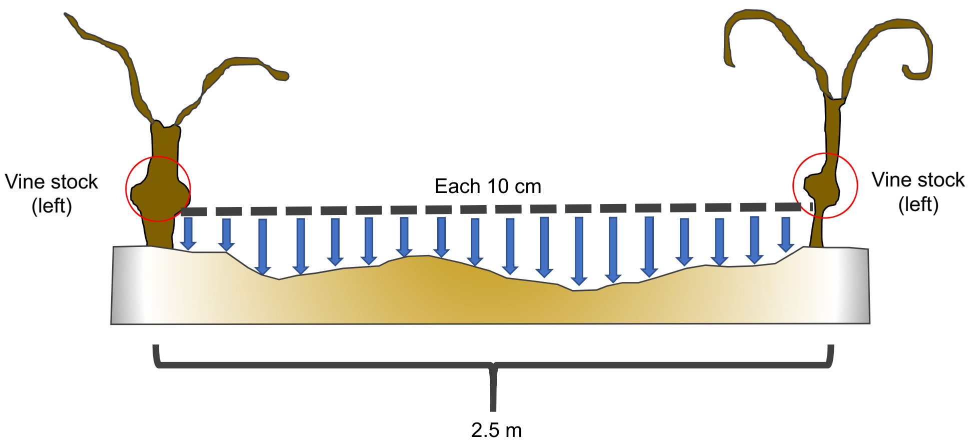

FIGURE 2 The scheme of the ISUM as applied in the study area, 26 measuring points at 10 cm intervals.

the ground level when planted (22 years ago). Thereafter the plant grows upwards and the soil could be eroded or deposited, making it possible to measure the distance between the current level of the soil and the graft (Casalí et al., 2009). Other measurements are made at relevant points along a line that joins two pairs of plants of opposite vines (Rodrigo-Comino & Cerdà, 2018). Measurements were carried out at 10 cm intervals within the inter-row area and at the vine stocks, the reference horizontal line being 50 cm above the current soil surface to identify footpaths, a wheel track or soil erosion features such as deposition areas or ephemeral rills.

This procedure was performed by stretching a measuring tape between opposite vines at the height where the graft joins (Rodrigo-Comino et al., 2019). ISUM was applied in two inter-row areas in March 2020 before the 39.8 mm rainfall (one event with a maximum rainfall intensity of 20.2 mm h^{-1}) and several tractor passes, and after this single event in May 2020. It is recommended that the measurements be carried out by the same researcher to avoid biases due to differences in the reading of the distance between the graft and the soil surface. In this study, 428 graft unions, 107 unions per row for 4 rows, were measured. The main objective of this type of methodology is to estimate the long-term soil movements (Biddoccu et al., 2018), allowing for the evaluation of changes in soil roughness, the impact of the slope on erosion, and making comparisons with other methods and study areas (Bayat et al., 2019). A Digital Elevation Model of the current soil surface level was created using ArcMap software (ESRI, USA), testing different interpolator tools such as ordinary kriging, inverse distance weighting, empirical Bayesian kriging, completely regularized spline, radial basis functions, spline with tension, multi-quadric, inverse multi-quadric and thin-plate spline. Ordinary Kriging yielded the highest R^2 and lowest root mean square error so it was the preferred one.

The results obtained in March 2020 and May 2020 in both measured inter-row areas were compared using SigmaPlot 12.0. All measurements taken at each location were used for the analysis. Statistical differences were analyzed using an ANOVA one-way test to determine whether there were any statistically significant differences between the means of the independent (unrelated) groups of ISUM values. If the Shapiro–Wilk normality and Levene's variance tests failed, a Tukey test was conducted. It needs to be acknowledged that the method has certain disadvantages. These include the assumption of no vertical growth of the vine graft union or movement after the initial plantation and the representativity of the bulk

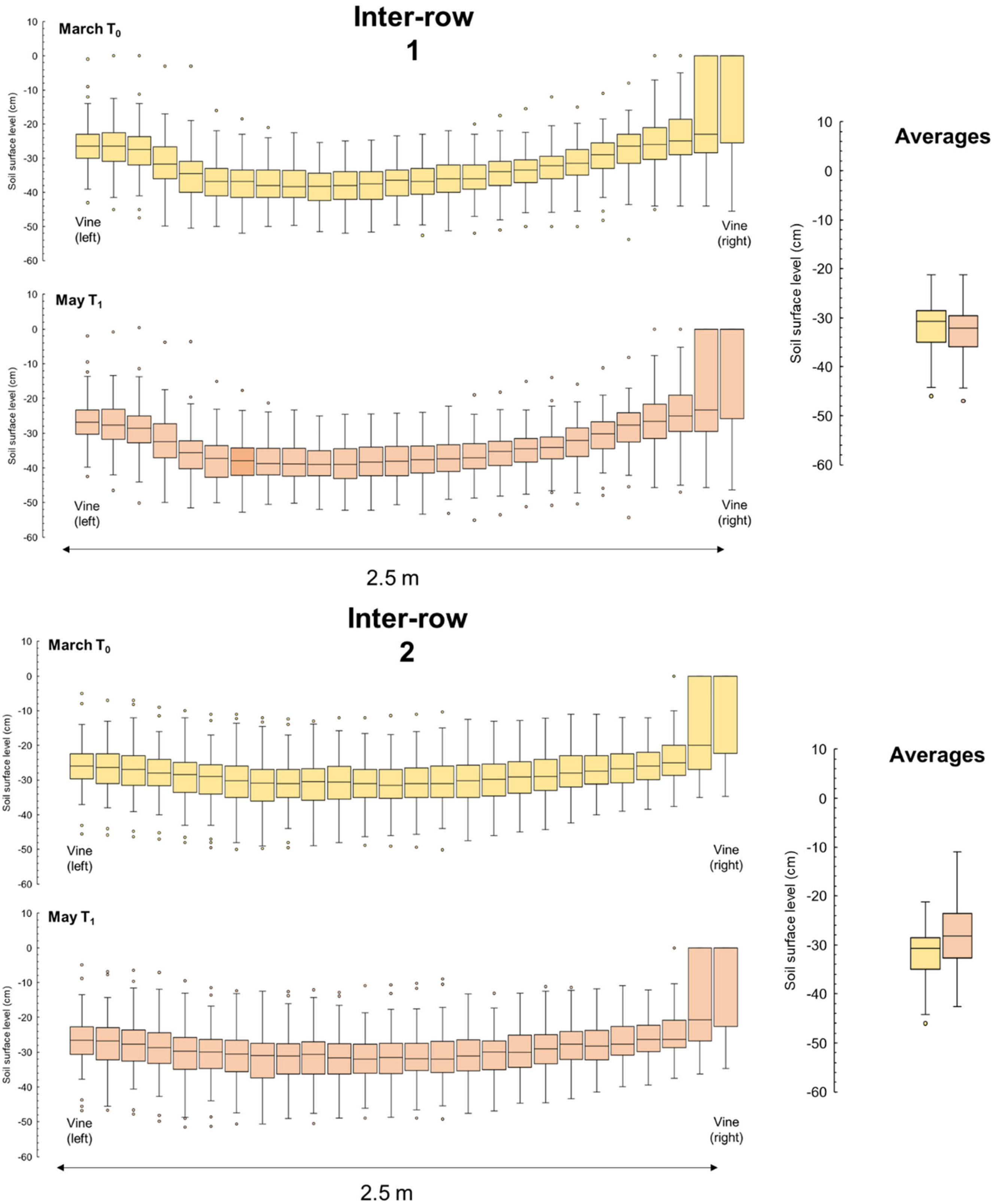

FIGURE 3 Boxplots of the cross-sectional profiles of the inter-rows 1 and 2 in March (T_0) and May (T_1).

density values along the plot used to model the surface for the final estimation of the soil erosion rates. In this research, we did not consider the margin of errors (+/− cm) of the ISUM measurements because we could not find recent plantations as examples to confirm after interviewing the farmers, but the graft union could vary as much as ±1 cm.

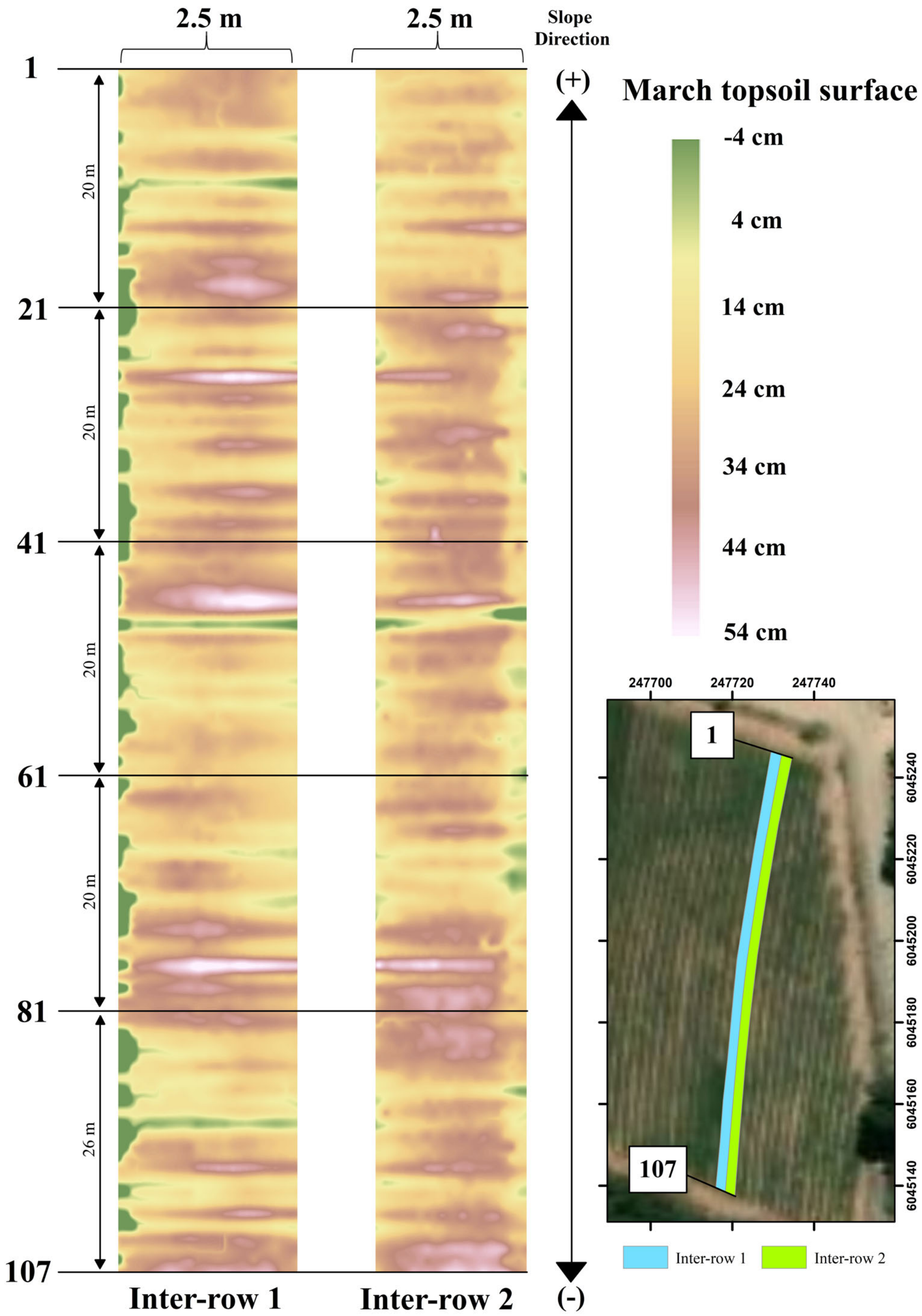

FIGURE 4 ISUM map of the local surface levels of the study area in March 2020.

2.2.2 | Annual erosion rate per hectare

The ISUM method estimates the changes in the soil level over a specified period for a specific area of the vineyard. The collected field data allow the calculation of the annual soil mobilization rate per ha, useful information for formulating proposals for planning and management strategies. To calculate the rate of erosion-deposition, the equation proposed by Paroissien et al. (2010) was applied:

$$\mathrm{ER} = \mathrm{V} \times \mathrm{BD} / (\mathrm{S} \times \mathrm{A}), \tag{1}$$

where the volume of mobilized soil (V, m^3) and the total area (S, ha) are obtained from the ISUM measurements. The soil bulk density (BD, g cm^{-3}) was determined from a total of 24 soil samples taken below the vines and in the inter-row areas using the ring method (each ring of 100 cm^3) and subjected to an air-drying process for at least 7 days. A value of 1.48 g cm^{-3} was obtained as an average. In Equation (1), A (years) is the total age of the plantation.

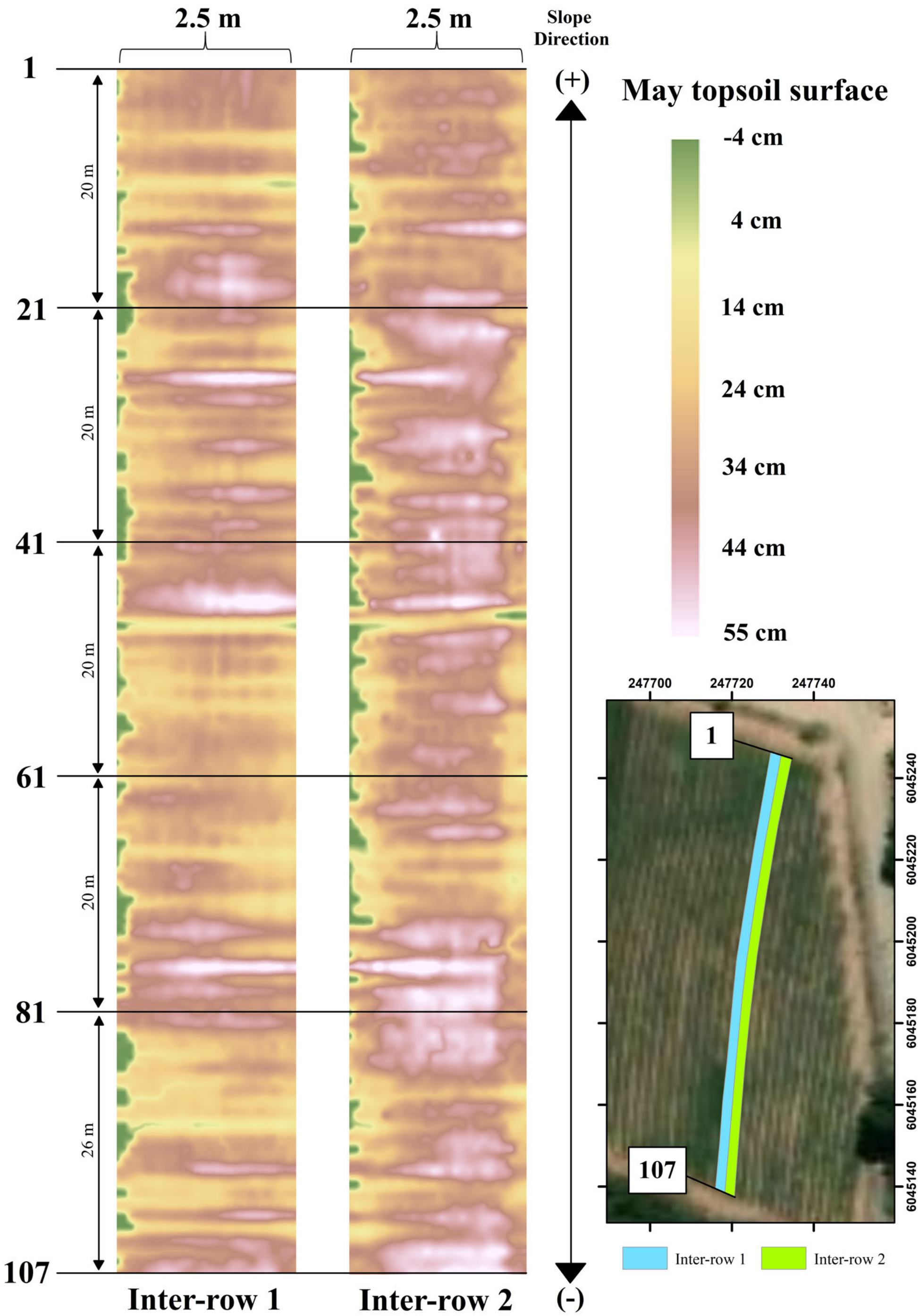

FIGURE 5 ISUM map of the local surface levels of the study area in May 2020.

3 | RESULTS

Figure 3 shows the boxplots of the cross-sectional profiles of opposite vine rows in March 2020 (T_0) and May 2020 (T_1). The results confirm that the soil surface level changed (Tukey test $p < 0.001$) significantly in both areas. In the inter-row area 1, the minimum cross-sectional profile change was −21.3 cm in March and −21.2 cm in May. The maximum mobilization rate was −46 cm in March 2020 and −47 cm in May 2020. For the inter-row area 2, the minimum and maximum values were −10.6 and −10.9 cm, and −42.3 and −42.7 cm, respectively, in March 2020 and May 2020.

Three surface-level maps were generated to represent the situation before and after the first rainfall event of the year and several tractor passes, and also the changes that occurred during the period. Figure 4 shows the soil level in the two inter-row areas before the rainfall season, that is, T_0 in March. Well-defined ephemeral rills are observed oriented perpendicular to the direction of the hillslope. These linear features correspond to the highest values in the measurements between the graft union and the soil surface (approximately 54 cm). Between these linear features, other areas can be observed that mostly cover both inter-row spaces and represent mean values in the measurements (approximately 24 cm). Finally, there are

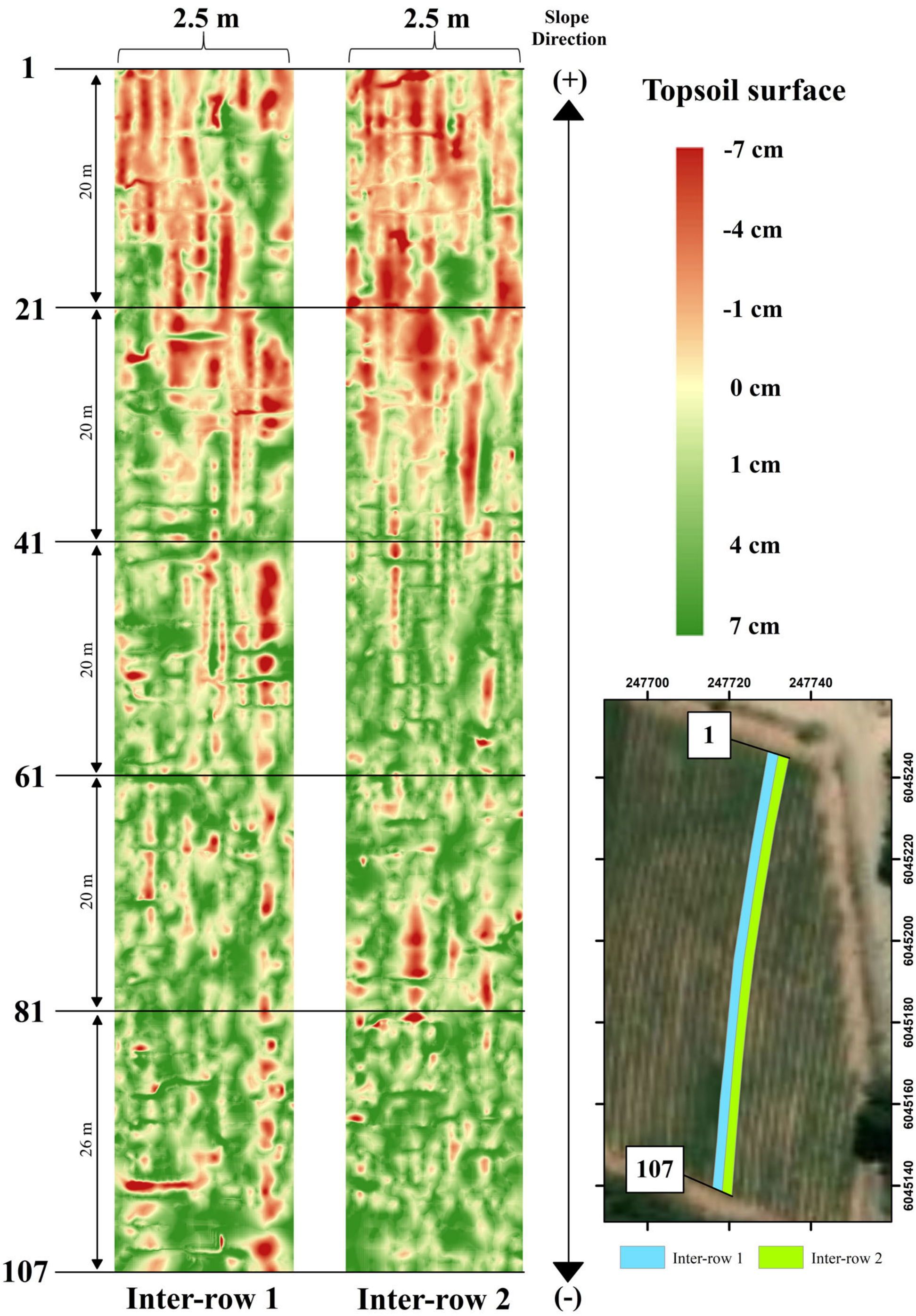

FIGURE 6 ISUM map of the total changes of the local surface levels of the study area between March and May.

small well-defined areas located on the left side of inter-row area 1 and the right side of inter-row area 2, representing the lowest values of the measurements (approximately −4 cm).

Figure 5 depicts the soil level in the two inter-row areas after the rainfall season in May 2020. It shows that the ephemeral rills are also oriented perpendicular to the hillslope (approximately −55 cm). Unlike Figure 4, a greater number of linear features were observed, and they are less defined and occupy a greater space. Surrounding the linear features in both inter-row areas are zones having average measurements reaching −24 cm. There are small areas located on the left side of both inter-row spaces that exhibit the lowest values in the measurements of approximately −4 cm, and they occurred after the recorded rainfall season.

The changes (surface level in May 2020 - surface level in March 2020) in the soil level of the two inter-row areas are shown in Figure 6. Negative values indicate high soil mobilization due to rainfall and tillage activities while positive values show soil accumulation due to sedimentation. In the inter-row area 1, erosion is mainly observed at the top of the row, concentrating on its left extreme and moving towards the centre and to the right as the slope decreases. In the same sections, an accumulation zone is also observed towards the right edge. As the slope decreases, the accumulation begins to increase, concentrating mainly on the left edge, except for an accumulation zone located in the middle of the row. From the middle section, the linear features are small and disaggregated, concentrating on the right edge. In the lower part, where the slope is lowest, an erosion zone is observed towards the right edge and also horizontally on the left edge. Accumulation is predominant and disaggregated in this section, concentrating mainly in the centre, and to a lesser extent towards the extreme end. The minimum surface level change is −6.7 cm (soil loss or erosion) while the maximum change is 6.1 cm (soil gain or accumulation). Both extremes are located towards the end of the inter-row zone.

For inter-row 2, the upper part experiences the greatest erosion coinciding with the highest slopes. Vertically oriented features are observed in the centre and on the left edge, and to a lesser extent on the right edge. There is also a prominent area of accumulation oriented to the right. Towards the middle of the row, small erosion zones that are oriented vertically are observed, one to the left and the other to the right. Accumulation begins to dominate in this part, appearing in irregular forms, but homogeneously distributed throughout the remainder of the inter-row area. Little or no erosion is observed towards the end of the hillslope, and it is distributed in only small areas. Accumulation is strongly predominant, and some concentrations are observed in the middle tending to the left in the last pairs of vines. Another important feature is in the lower-left corner. The minimum change is −5.8 cm (soil mobilization) while the maximum change is 5.7 cm (soil accumulation), both extremes occurring towards the end of the row.

The ISUM measurements indicate that there is soil loss in both inter-row areas. Our results showed a total soil mobilization of 85.7 and 130 Mg ha yr^{-1}, respectively, in the inter-row areas 1 and 2 during the total years since the plantation has been in existence (22 years). In inter-row area 1, the total volume of soil mobilized by the rainfall event was 2.19 m^3 over a total area of 0.027 ha. This translates to 3.25 Mg, which represents a mobilization rate of 5.46 Mg ha yr^{-1}. In the inter-row area 2, the volume of soil mobilized was 1.38 m^3, which translates to 2.04 Mg, representing 3.44 Mg ha yr^{-1} of soil mobilization.

4 | DISCUSSION

ISUM maps allow the determination of areas experiencing the highest values of erosion/deposition. Our results showed that the critical areas are located mostly in the central parts of the inter-row areas, corroborating other research that confirmed that the drainage is from both vine rows to the centre (Fressard et al., 2022; López-Vicente et al., 2020). The reason is that soil compaction and redistribution of materials generated by machinery, animals, and people occur in the inter-rows of vines (Biddoccu et al., 2018; Bogunovic et al., 2020). In the inter-row area 1, the minimum values are located on the left side, which could be attributed to the slope that falls in an east–west direction. The vines act as a barrier, which allows materials to accumulate at the base of the plant instead of moving down the slope, as demonstrated by other authors in Spain using connectivity assessments (Rodrigo-Comino et al., 2018). Unfortunately, there is no topographic cross-section (or slope map) to give a better idea of the slope morphology which could help explain the location of erosion and deposition areas along the hillslope. Drones are being considered for deriving a topographic cross-section in a new ISUM research to augment data acquisition for regions lacking high-resolution digital elevation models.

In the derived ISUM maps, the areas with the highest erosion/deposition values are less defined and spread out, particularly for the inter-row 2. The alteration of the soil due to changes in organic matter and soil moisture contents, and subsequently, the reduction in the bulk density and aggregate stability due to the action of extreme rainfall events could be some of the contributing factors. In both plots, the highest soil mobilization and erosion features occurred in the upper part, which could be due to the effect of slope and roughness. A steeper slope generates higher rates of erosion as the competition of flows is favoured over infiltration, the velocity of sediment and water is also higher, and the generation of ephemeral rills occurs (Badía et al., 2013; Bagio et al., 2017).

In these vineyards, the upper parts of both rows of vines have the highest slopes that decrease downstream. Thus, the runoff has a greater erosive power due to higher speed, which increases its competence and its ability to carry sediments, enhanced by the tractor passes and extreme rainfall events (Arnaez et al., 2011; Ferrero et al., 2005). In the lower part of both rows, the water slows down or ponds due to the low slope. This reduces its ability to carry sediments, and thus deposition occurs. In this research, the connectivity processes due to tillage and rainfall events have been demonstrated (Fressard & Cossart, 2019; López-Vicente & Ben-Salem, 2019).

The minimum and maximum values of mobilization rates in both inter-row areas occurred towards the end, specifically where the slope is lowest. The maximum values indicate the accumulation of sediments and their location agrees with the shape of the terrain and the slope of the lower section. Conversely, the minimum values indicate soil depletion. However, the minimum values are not located in the sections where the greatest erosion occurred but on the lowest slope, where accumulation is predominant. This could be due to the stagnation of the water given that the slope is not high enough for surface runoff generation. The water ponds in the lower parts, wearing down the weakest materials as the precipitation intensifies. When the intensity of precipitation decreases, water that flows through sediment-laden surfaces accumulates in depressed areas or those previously eroded (Cantón et al., 2011). At the top of the hill, where the largest areas of erosion were observed, the slope is high enough for the water to run off and not to concentrate in puddles, eroding in vertical strips that follow the direction of ephemeral gullies and rills (Capra et al., 2009; Casalí et al., 2006).

There were also multiple erosion zones located towards the edges, which could be caused by the shape of the land engineered by the presence of the vine plants. The vines were planted on an artificially created mound of earth. This generates a micro-topography that modifies the natural surface runoff. The water that reaches the ground by cortical runoff flows through the mound to the pond at its upstream (Cogo et al., 1983; Ding & Huang, 2017; Govers et al., 2000). The slopes of the mound generate erosion at the edges with an elongated shape parallel to the slope. A higher slope increases the concentration of flows and thus erosion. Some authors indicate that erosive processes usually start from 10°, that is, a slope of 17.6% (Armstrong et al., 2011; Benisi Ghadim et al., 2020; Bryan & Wijdenes, 1992). Thus, the slope values present in the study area are enough for instigating erosive processes.

One key question is related to the sediment budget of the cross sections following the different precipitation events, and it is necessary to assess the consistency between eroded and deposited volumes. In Figure 4, it is observed that the deposition area occupies a much larger surface than the erosion area, and it is imperative to verify whether the volumes involved in erosion and deposition are equivalent or not. The results could shed light on whether there is sediment export from the plot or sediment supply from the upper part (shoulder), and also the margin of error of the ISUM methodology. In addition, some extra measurements considering the upslope connectivity of the investigated plot could give us new information about the upslope accumulated runoff flux that may enter the plot, and thus favouring the occurrence of erosion, or otherwise.

Erosive processes are naturally common in mountainous environments where the shape of the land and the slope are the main determining factors (http://www.fao.org/soils-portal/soil-degradation-restoration/en/). The Melozal sector (where the studied vineyard is located) is characterised by its gentle slopes, surrounded by the morphology corresponding to the eastern flank of the coastal mountain range. Given the human impacts on the study area, it is not possible to confirm the presence of natural erosive processes in the analyzed sector and its surroundings. Generally, erosion is diminished or increased depending on the prevailing management practices. Other factors that determine erosive processes relate to the climate such as the impact of rain on the soil and its ability to mobilise particles, but the key is the human factor (Cerdà, Novara, et al., 2021; Taguas et al., 2015). As described above, the meso-climate of the commune is characterised by annual precipitation values of between 800 and 1000 mm (Illustre Municipalidas de San Javier, 2018), which are concentrated between May and September, and represent 78.5% of the annual total. However, during the studied period (3 months) the accumulated rainfall reached a total of 39.8 mm, the maximum of which occurred in May. Normally, rainfall begins after the dry period in April and then increases abruptly in June.

Soil cover is also a determining factor of erosion due to its influence on infiltration (Bradford & Huang, 1994; Chau & Chu, 2018; García-Díaz et al., 2017). Greater infiltration makes it difficult to generate surface runoff with enough erosive capacity. Less infiltration leads to increased surface runoff and erosion. In the study area, the vegetation cover is limited given its land use. Vine plantations, by themselves, have a low foliar surface, which disappears in the winter months precisely when high-intensity rainfall occurs. In the inter-row areas, the presence of a small vegetation cover, mainly weeds, could help to mitigate erosion. Although these weeds are currently being controlled by cattle grazing, the application of chemicals to eliminate them will expose the soil and increase erosion in the medium and the long term (Okur et al., 2016; Peregrina, 2016; Pijl, Tosoni, et al., 2019).

The infiltration capacity of the soil is related to its physical characteristics, such as the texture, structure, and stability of the aggregates. A good aggregation keeps the soil particles together, allowing the water to flow through. However, if the aggregates are dispersed, the pores get clogged and infiltration is reduced resulting in high surface runoff. The sandy clay loam texture soils of the Melozal sector are characterised by having good drainage and, therefore, a low water retention capacity (Instituto Nacional de Investigación de Recursos Naturales, 1979). It has been observed that the erosion rates obtained in the present study exceeded the rates of soil formation. A tolerable erosion can be defined as the maintenance of the dynamic balance of the amount of soil (mass/volume) in any place and under any circumstance (Verheijen et al., 2009). In this sense, numerous researchers have agreed that, in the case of Europe, the rates of erosion in soils subjected to arable use are between 10 to 20 Mg ha^{-1} year^{-1}. However, the erosion rates in this area after some rainfall events even exceeded the annual tolerable levels. Our results are extremely useful to analyse and compare the erosive process that occurs in the study area with other places in Chile and the world. Thus, this research can contribute to the generation of future actions that protect the soil as a resource, considering its uses and management. The merits of this type of research depend on the space–time scale analyzed and the characteristics of each study. To date, there is a lack of studies where soil mobilization rates related to specific rainfall events with this resolution are calculated. The results obtained in this study are useful to determine how the erosive process is affecting vine plantations in the short and medium term. The final aim is to establish strategies to mitigate the negative effects of erosion by protecting the soil resource and increasing the productivity of the vineyard. Our results could be used in vineyards with similar characteristics, as measurements for this type of work take too much time and resources. This would be extremely useful for small and medium-sized local wine entrepreneurs who do not always have the financial resources, the workforce, the knowledge, or the time necessary to implement such studies. The applicability of this work in places with similar characteristics allows the local viticultural activity to be promoted, especially in the context of climate change that affects factors that contribute to the erosive processes. Knowing how this process works in vineyards could allow local entrepreneurs to improve the conditions of their crops and, therefore, improve their production.

In Chile, studies aimed at analyzing the behaviour of erosion have focused mainly on using direct methods or indirect estimations. We would like to highlight that the investigations and results are based on two adjacent cross sections, which could raise the question of the representativeness of the results at other sites having different specific conditions or general conditions. Hence, complementary investigations in different topographic or soil management conditions are paramount. Given the amount of data required by the ISUM methodology, large-scale applications, for example, at catchment scales, could be challenging.

5 | CONCLUSIONS

The application of the ISUM approach has allowed the development of maps that represent the ground level of the inter-row spaces in March 2020 (before the first rainfall event) and May 2020 (after the first rainfall event), and also the changes in the ground level during this period. Eroded and sedimentation areas were apparent from the developed maps. Erosion rates of -5.5 Mg ha^{-1} year^{-1} (first plot inter-row space) and -3.5 Mg ha^{-1} year^{-1} (second plot inter-row space) were estimated. It has been determined that the main factors influencing the results were precipitation, soil management, slope angle and geometry. These factors have influenced the erosive processes present in the study area, which exceeds the rates of soil formation, and the tolerable rates of erosion at the global level (less than 0.4–1.3 Mg ha^{-1} yr^{-1}). It has been demonstrated that this method is effective for the calculation of erosion rates in vineyards. Finally, the need for future studies that address the management of soils used by viticulture arises, suggesting appropriate forms of management depending on the characteristics of each region. The relevance of this economic activity, and its importance as cultural heritage, calls for the need to re-thinking soil management systems.

ACKNOWLEDGEMENTS

We would like to thank the owners of Viña Saavedra, in the Melozal sector of the San Javier commune (Maule region, Chile) and colleagues that helped us to conduct this research in the field. This work was produced with the support of a 2021 Leonardo Grant for Researchers and Cultural Creators and BBVA Foundation and is gratefully acknowledged. Also, we want to thank the SI3/PJI/2021-00398 project granted by the Comunidad Autónoma de Madrid.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Google Drive at https://docs.google.com/spreadsheets/d/1bXe4HlwtRJv7wcfzZGqH5KgfVp7PrkqE/edit?usp=sharing&ouid=103427877078986367218&rtpof=true&sd=true.

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How to cite this article: Lozano-Parra, J., Maldonado-Clavelle, C. F., Caballero-Calvo, A., Pulido-Fernández, M., Gyasi-Agyei, Y., & Rodrigo-Comino, J. (2023). Estimation of soil mobilization rates by a rainy period and intense tillage practices in vineyards—A case study in the Maule region (Chile). *Hydrological Processes*, *37*(4), e14829. https://doi.org/10.1002/hyp.14829