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Spatial Variability and Magnitude of Soil Erosion in Vineyards Across Spain: Insights from Standardized ISUM Measurements

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Abstract

Soil erosion and sediment redistribution in vineyards often exceed tolerable thresholds, but comparative field measurements across regions remain limited because studies use different methods and sampling designs. This study assesses soil redistribution in vineyards using a common field-based approach. Thirteen vineyard sites across Spain, covering contrasting climates, parent materials, soil types, management conditions, and vineyard ages (2–40 years), were surveyed using the Improved Stock Unearthing Method (ISUM). Soil surface changes were measured along systematic transects and combined with site-specific bulk density and vineyard age to estimate soil mobilization rates in t ha^{-1} yr^{-1}. Measured surface changes ranged from −28 to +19 cm, while soil mobilization rates varied

considerably among sites. The highest net soil losses were recorded in a young vineyard developed on limestone (-103.3 t ha^{-1} yr^{-1}) and in a vineyard on marls (-87.7 t ha^{-1} yr^{-1}). Other sites showed moderate net erosion (-3.9 to -15.4 t ha^{-1} yr^{-1}), whereas positive balances (+7.2 to +17.9 t ha^{-1} yr^{-1}) were observed in some older or more stable vineyards. Differences among sites suggest that vineyard age and parent material are relevant factors when interpreting erosion magnitude, while management conditions may contribute to the spatial variability of soil redistribution. Spatial maps based directly on ISUM measurements showed marked differences between erosion and deposition areas within individual vineyards, without the use of spatial interpolation. Applying the same ISUM protocol across contrasting vineyard conditions allowed soil redistribution patterns to be compared using a consistent field procedure. The results also showed the large variability that can occur among vineyard systems.

Keywords: soil mobilisation; viticulture; Improved Stock Unearthing; regional studies; Spain

1. Introduction

Soil erosion is widely recognized as one of the most severe forms of land degradation worldwide, threatening soil functions, ecosystem services, food security, and long-term agricultural sustainability [1,2]. In Europe, soil erosion has gained renewed attention due to its strong links with climate change, biodiversity loss, and water quality deterioration. Recent European Union initiatives, including the upcoming Soil Monitoring Law, the Green Deal, and the Common Agricultural Policy, emphasize the urgent need for reliable, spatially explicit, and comparable data to assess soil degradation processes [3]. Recent remote-sensing studies further highlight the importance of spatially explicit approaches for understanding erosion-prone landscapes. In Mediterranean environments, for example, Sannino et al. [4] and Alatorre and Beguería [5] showed that climate variability and land-cover transformations can jointly influence vegetation dynamics and geomorphological stability in rural landscapes affected by badlands. At a broader agricultural scale, Chen et al. [6] demonstrated the value of integrating field surveys with multi-source land-use and land-cover data to assess the spatial and temporal dynamics of cropland soil erosion. In this context, initiatives such as Living Labs [7] and large-scale monitoring programmes [8,9] can play a key role in supporting evidence-based decision-making and highlighting the importance of harmonized methods to quantify erosion processes across different landscapes and land-use systems [10].

Agricultural land is among the most erosion-prone environments, where soil loss rates often exceed those observed under natural ecosystems [11]. In cultivated fields, erosion is driven by a combination of anthropogenic and natural factors [12–14]. Human-related drivers include soil disturbance by tillage [15] or the maintenance of bare soil conditions [16], which reduce surface protection and soil structure stability [17]. In addition, degraded soil becomes more susceptible to further erosion due to a decline in soil cohesion, loss of organic matter, and reduced water infiltration [18]. The interaction between natural and human drivers results in high spatial variability in erosion rates within and between agricultural systems. Among cultivated systems, vineyards have repeatedly been identified as erosion hotspots, particularly in Mediterranean regions [2,19,20], mainly because they are often located on sloping terrain, managed with frequent soil disturbance, and maintained with limited vegetation cover between rows [21]. These characteristics, combined with intense rainfall events, promote both soil detachment and sediment redistribution along inter-rows [22,23]. In some cases, the arrangement of rows and inter-row areas parallel to the

steepest slope direction can significantly increase sediment connectivity and, consequently, sediment delivery outside the field [24]. As a result, vineyards frequently exhibit some of the highest erosion rates reported in agricultural landscapes, making them a key system for studying erosion dynamics and testing monitoring approaches.

Numerous field-based studies across Europe, including in Spain, one of the world's leading grape-producing countries, have documented severe soil erosion in vineyards, with reported erosion rates often exceeding commonly accepted tolerable thresholds [25]. For instance, field measurements in Mediterranean vineyards have reported mean annual erosion rates ranging from 5 to more than 30 t ha^{-1} yr^{-1}, with extreme values locally exceeding 40 t ha^{-1} yr^{-1}, particularly under bare-soil management and on steep slopes [26]. Plot- and field-scale studies in Spanish vineyards have shown erosion rates between 10 and 60 t ha^{-1} yr^{-1}, depending on slope gradient, rainfall regime, and inter-row management practices. These studies highlight substantial spatial variability at plot and hillslope scales, controlled by local topography, soil properties, management practices, and rainfall regimes [27,28]. While this growing body of literature clearly demonstrates the magnitude of erosion in vineyards, direct comparisons across regions remain challenging due to differences in methodological approaches, temporal coverage, and sampling designs.

Despite the availability of reviews and meta-analyses synthesizing erosion rates in vineyards and agricultural systems in Spain (e.g., [29]), methodological heterogeneity remains a major limitation. Erosion measurements are often based on different techniques, temporal windows, and seasonal conditions, which hampers direct comparability among studies. This lack of standardization constrains the assessment of spatial variability and the identification of dominant erosion controls at larger scales. In this context, the Improved Stock Unearthing Method (ISUM) represents a robust and cost-effective field-based approach for assessing soil erosion and sediment accumulation in vineyards [30]. Originally developed to quantify soil surface lowering and sediment redistribution along vine interrows [31,32], ISUM has been successfully applied in a wide range of European vineyard systems, particularly in Mediterranean environments, and has also been used for other woody crops (e.g., [33]). Previous studies have implemented ISUM in vineyards located in other countries [34], demonstrating its ability to capture fine-scale spatial variability in erosion and deposition processes under contrasting slope gradients, soil types, and management practices. ISUM measurements have been used both as a standalone method and in combination with other field techniques and spatial analyses, proving especially suitable for comparative studies due to its standardized protocol, repeatability, and low operator dependency [35]. As ISUM simultaneously accounts for erosion and accumulation patterns along inter-rows, it provides valuable insights into sediment mobilization processes that are often overlooked by conventional erosion assessment methods such as rainfall simulations or erosion plots.

The main objective of this study is to assess and compare the spatial variability of soil erosion and sediment redistribution in vineyards across Spain using standardized ISUM measurements. Thirteen vineyard sites distributed across different physiographic gradients were surveyed using a common protocol applied by the same research team to minimize operator-related bias and ensure methodological consistency. By adopting a uniform data-processing workflow, this study aims to provide a robust comparative assessment of erosion rates under contrasting environmental and management conditions. Specifically, we test the following hypotheses: (i) soil erosion rates in vineyards show pronounced spatial variability across Spain, driven by differences in topography, climate, and management practices; (ii) management-related factors exert stronger control over erosion variability than climatic factors at the scale considered; and (iii) standardized

ISUM measurements enable consistent comparison of erosion and accumulation patterns, allowing the identification of dominant erosion controls across vineyards.

2. Materials and Methods

2.1. Study Areas

The study was conducted across thirteen vineyard sites distributed throughout the Iberian Peninsula and the Balearic Islands, covering a wide range of climatic and topographic conditions, lithologies, soil types, vineyard ages, and management strategies (Figure 1). The selected sites span Mediterranean, semi-arid, continental, Atlantic, and continental–oceanic climates, with mean annual rainfall ranging from <300 mm in Padul (Granada) to >1100 mm in Betanzos (A Coruña) and mean annual temperatures ranging from 12.5 to 17.3 °C (Supplementary Materials Table S1). This spatial distribution allows soil erosion to be assessed under contrasting environmental gradients representative of major wine-growing regions in Spain.

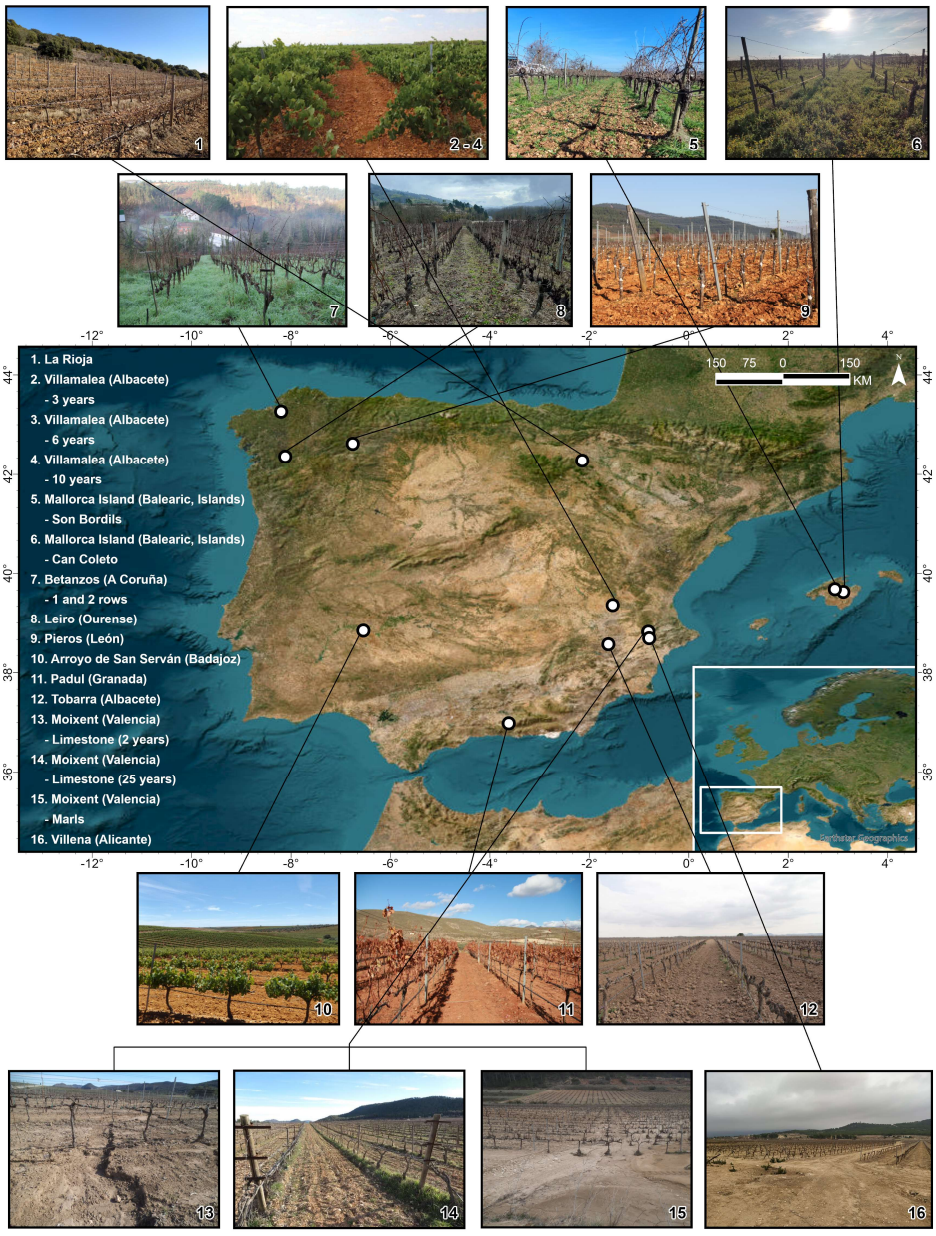


Figure 1. Localization of the study areas.

Lithology and soil types vary markedly among sites, including limestones and marls (Moixent), detrital deposits (Mallorca Island and Villena, Alicante), schists (Betanzos, A Coruña), granites (Leiro, Ourense), fluvial gravels (Arroyo de San Serván, Badajoz), and mixed sandstone–conglomerate formations (La Rioja and Tobarra, Albacete). Soils are mainly classified as Cambisols, Luvisols, Anthrosols, and Calcisols according to IUSS-WRB [36], reflecting different stages of pedogenesis and management-induced soil modification (Supplementary Materials Table S1). Topography ranges from flat or gently sloping vineyards (<2%) in Villamalea (Albacete), Villena, and Tobarra to steep slopes exceeding 30% in Betanzos, with intermediate conditions in Padul and Leiro. A key feature of the dataset is the strong contrast in vineyard age, which ranges from recently established plantations (2–3 years) to long-term vineyards older than 25 years. Different ages of plantations are explicitly represented in Moixent, Valencia (limestone vineyards of 2 and 25 years); Villamalea (3, 6, and 10 years); and Mallorca Island (24–26 years), allowing the evaluation of temporal effects on soil surface dynamics. Vineyard management practices include conventional tillage, organic management, permanent or partial vegetation cover, and residue retention, with row spacing varying between 1.7 and 3.0 m and transect lengths ranging from ~30 to ~190 m (Supplementary Materials Table S2). All vineyards follow a trellis planting system. All study sites were surveyed following the same ISUM protocol and data-processing workflow (Figure 2), ensuring methodological consistency and minimizing operator-related bias. This harmonized experimental design provides a robust basis for cross-site comparison of soil surface change, erosion rates, and spatial redistribution patterns under field conditions.

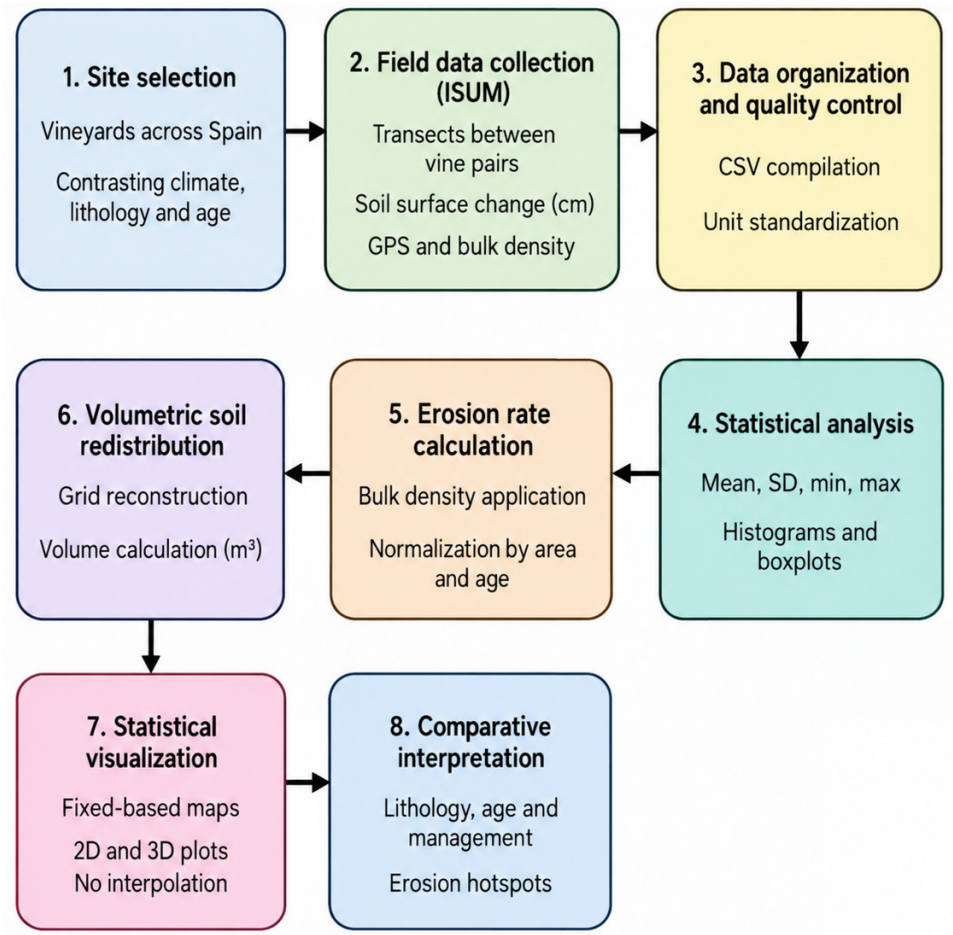


Figure 2. Flowchart designed to reproduce ISUM and comparisons.

2.2. Field Data Collection

For each vineyard, the monitored area was delimited by recording four GPS control points (lower left, lower right, upper left, and upper right) using an EMLID Reach RS+ to frame the study plot. Control points were measured in the field in 2022 and 2023 and later exported to Geographic Information System (GIS) formats (e.g., .shp and .csv) to ensure consistent spatial referencing of all measurements. Soil surface level changes were quantified using ISUM, which uses the graft union of grafted vines as a passive bioindicator. This approach relies on the assumption that graft unions do not grow vertically, making them suitable reference markers for estimating long-term soil surface changes. The field procedure followed the standard ISUM cross-sectional survey approach. For each pair of vines, a tape was stretched and raised to a fixed height (commonly 30 cm) to standardize measurements and avoid bias. The distance from the reference tape to the soil surface was measured at regular intervals of 10 cm along the transect. The first three study areas surveyed with ISUM, which included only five measurements per transect (every 0.5 m), were also included as a reference for the evolution of the method and to ensure methodological continuity (more information can be found in [37,38]). Transects were repeated systematically across the plot to obtain high-resolution coverage; for example, in Padul (Granada), measurements were taken every 10 cm, reaching a total of 2714 points within 0.03 ha (118 paired vines $\times$ 23 measurements), which were later used to map the soil surface level. Measurements can be taken in both row and inter-row contexts. Some implementations use a second tape height in inter-rows (e.g., 20 cm above the graft) to minimize problems associated with buried unions, depending on site conditions. Field notes were recorded for anomalies such as stones, steps, roughness, and missing vines, and photographic documentation was collected to support interpretation and QA/QC.

Surface conditions were visually inspected during each survey to identify local disturbances that could affect the position of the measured soil surface. Particular attention was paid to conditions potentially associated with recent tillage or temporary changes in surface roughness, as these can influence individual ISUM measurements. Measurements were avoided immediately after intense rainfall events or recent tillage operations to minimize temporary changes in soil moisture, surface roughness, and microtopography that could affect the measured soil surface level. Field notes were recorded for anomalies such as stones, local steps, roughness, disturbed soil, and missing vines. Photographic documentation was also collected to support interpretation and quality control.

2.3. Data Processing and Generation of Erosion Metrics

Bulk density (BD) was measured using cylindrical ring sampling and was used to convert soil surface changes into mass-based erosion/deposition rates [39]. Bulk density was determined from 24 independent soil cores of 100 cm^3 collected in each vineyard. Sampling locations were randomly selected across the surveyed area and included both under-vine and inter-row/tractor-pass positions to capture small-scale spatial heterogeneity. Samples were collected from the upper 0–15 cm soil layer, which represents the surface soil directly involved in the erosion–deposition processes assessed by ISUM. No subsamples were combined, and deeper soil layers were not analysed. The resulting set of measurements was used to characterize bulk density variability within each vineyard and to obtain a representative value for converting soil volume into mass.

ISUM produces point-based measurements of soil surface change relative to the graft union reference. Values were interpreted as (i) negative, indicating soil depletion (erosion), and (ii) positive, indicating soil accumulation (deposition). Annual soil mobilization rates were computed using the erosion–deposition equation [40], combining (i) Vol, the net volume of depleted/accumulated soil (m^3); (ii) bulk density (g cm^{-3}); (iii) St, the plot area

(ha); and (iv) Av, the reference period/vine age (yr). Operationally, the calculation involved estimating volume (Vol) by integrating point measurements over the surveyed plot surface using grid or rectangular cells defined by the measurement spacing. The resulting volume was converted to mass using the measured bulk density (mass = volume × BD) and then normalized by plot area and the reference period/vine age (Av) to obtain soil mobilization rates in t ha^{-1} yr^{-1}. Descriptive statistics (mean, median, SD, minimum, and maximum) were calculated for each dataset, and distributions were summarized using histograms and boxplots.

2.4. Statistical Analysis and Visualization of ISUM Data

ISUM datasets were analysed using descriptive statistics and graphical methods to characterize the magnitude, distribution, and variability of soil erosion and deposition within each vineyard. All analyses were conducted in Python, ensuring transparency and reproducibility. Data were stored in CSV format and imported using the pandas library. Negative values represent soil loss (erosion), whereas positive values indicate soil accumulation (deposition). Numerical operations were performed with NumPy, and graphical outputs were generated using Matplotlib, with Plotly employed for selected interactive visualizations. For each vineyard, descriptive statistics—including mean, median, standard deviation, minimum, and maximum—were calculated to summarize soil surface changes. The relationship between mean and median values was used to evaluate distribution symmetry and potential skewness towards erosion or deposition.

Histograms were constructed to examine the frequency distribution of ISUM values, using regular class intervals adapted to the data range of each site. These plots facilitate the identification of dominant processes, distribution asymmetry, and extreme erosion or deposition values. Boxplots were used to provide a robust summary of ISUM distributions, displaying medians, interquartile ranges, whiskers, and outliers. This approach allowed comparisons between transects within individual vineyards and among different sites, highlighting spatial heterogeneity and systematic soil loss where median values were predominantly negative. Statistical analyses were interpreted together with spatial visualizations derived from ISUM data. Two-dimensional representations were generated to link numerical patterns with their spatial expression across vineyard surfaces, supporting the identification of erosion hotspots and depositional zones. Spatial processing and mapping relied on GeoPandas, Shapely, and leafmap, enabling the integration of ISUM measurements with georeferenced vineyard boundaries and the creation of interactive maps, which are provided as supplementary online material (https://www.egemap.eu, accessed on 29 July 2026).

3. Results

3.1. Frequency Distribution of ISUM Values

Histograms in Figure 3 show the frequency distribution of soil surface change values (cm) obtained with ISUM for all study areas. Young vineyards developed on limestone show the most extreme distributions, particularly the limestone site (2 years) in Valencia, where erosion values reach a minimum of −17 cm and deposition peaks at +16 cm, resulting in a wide and nearly symmetrical distribution centred close to zero but with very high dispersion (SD = 4.42 cm). In contrast, the limestone site (25 years), also in Valencia, displays a clear shift towards positive values, with a mean surface change of +2.72 cm and a reduced erosion tail (minimum −11 cm), resulting in a distribution dominated by positive soil surface-change values and a comparatively shorter erosion tail. Marls (8 years) in Valencia present the most erosion-dominated distribution of all sites, with pronounced negative skewness, a minimum value of −19 cm, a mean of −4.91 cm, and

limited positive values (maximum +8 cm), reflecting intense and spatially consistent soil loss. Intermediate patterns are observed among the Villamalea vineyards (3, 6, and 10 years) in Castilla-La Mancha, where the distributions progressively narrow and shift from erosion-dominated to more balanced conditions. The 3-year site exhibits a clear dominance of erosion (mean −1.29 cm; minimum −10.8 cm), while the 6-year vineyard shows values clustered around zero (mean −0.02 cm), and the 10-year site displays a positive shift (mean +1.61 cm), showing a progressive change in soil surface values across the three vineyard ages. Marked contrasts also emerge among sites with different management and environmental conditions. On Mallorca Island, Can Coleto shows a narrow distribution centred near zero (mean +0.28 cm), whereas Son Bordils exhibits a broader, erosion-dominated pattern (mean −1.86 cm; minimum −14.9 cm). Atlantic vineyards in A Coruña and Ourense display consistently negative distributions, while Mediterranean continental sites such as Arroyo de San Serván (Badajoz, Extremadura) and Tobarra (Albacete, Castilla-La Mancha) record high variability and extreme values (up to −28 cm and +19 cm in Badajoz). Overall, the histograms show marked site-specific differences in soil redistribution patterns that cannot be adequately represented by mean soil mobilization rates alone.

3.2. Spatial Distribution of ISUM-Derived Soil Surface Changes

In Figure 4, the panels depict the pixel-scale spatial distribution of soil surface changes. The maps are based exclusively on measured values and do not involve spatial interpolation, thereby preserving the measured pixel-scale variability of soil redistribution. The spatial distribution maps derived from ISUM measurements reveal strong heterogeneity in soil redistribution within and among vineyards, with clear contrasts in both the magnitude and spatial organization of erosion and deposition patterns. In young vineyards on limestone in Valencia, extreme values are spatially clustered, particularly in the 2-year site, where soil surface change ranges from −17 cm to +16 cm, with erosion hotspots concentrated along specific inter-rows and depositional zones occurring downslope. In contrast, the 25-year limestone vineyard in Valencia shows a more organized spatial pattern, with predominantly positive values (up to +17 cm) and limited erosion areas (minimum −11 cm), with positive soil surface-change values occurring more widely than in the younger limestone vineyard. The marl site in Valencia exhibits the most erosion-dominated spatial configuration, with widespread negative values across the vineyard and maximum soil lowering reaching −19 cm, while depositional areas remain scarce and spatially restricted (+8 cm).

Differences among the three vineyard ages are evident in Villamalea. The 3-year vineyard displays extensive erosion patches (minimum −10.8 cm) distributed across most of the field, whereas the 6-year site shows a more balanced mosaic of erosion and deposition (−9 to +8.5 cm). In the 10-year vineyard, depositional areas are more frequent and spatially continuous, with positive values reaching +12 cm and erosion becoming more localized (minimum −9.4 cm). Mediterranean vineyards such as Villena (Alicante) and Tobarra (Albacete) present marked spatial contrasts, with erosion values down to −9.9 cm and −14.2 cm, respectively, and limited depositional zones. In Badajoz (Extremadura), the greatest spatial variability is observed, with extreme soil loss reaching −28 cm and accumulation up to +19 cm, resulting in the widest range of soil surface-change values among the studied vineyards. Atlantic vineyards in A Coruña and Ourense show more uniform but consistently negative patterns, whereas Padul (Granada) and La Rioja display mixed but spatially structured patterns, with maximum values of +18.8 cm and +19 cm, respectively.

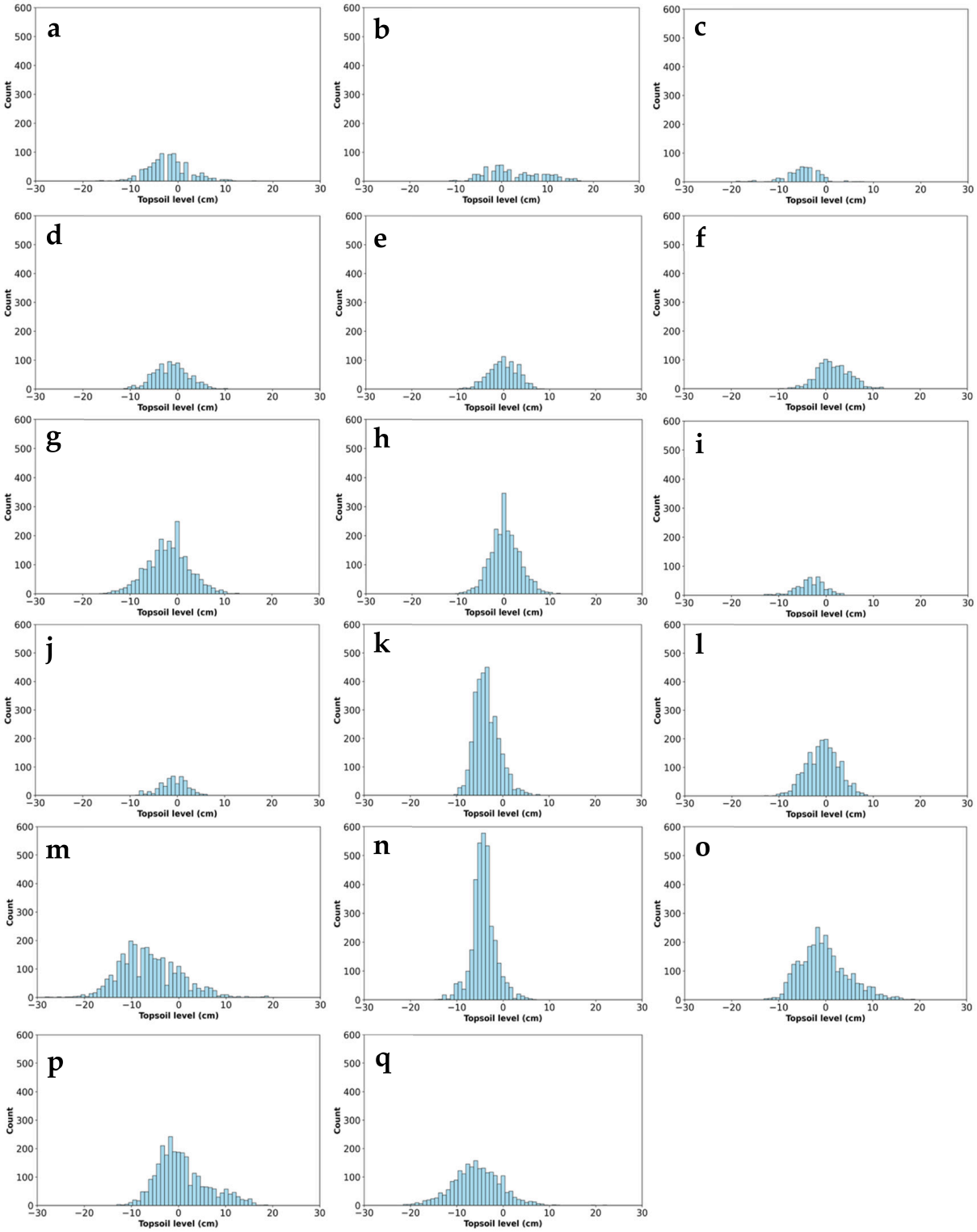


Figure 3. Frequency distribution of ISUM-derived soil surface change. The panels are ordered from (**top**) to (**bottom**) and (**left**) to (**right**) as follows: (**a**) Limestones (2 years), (**b**) Limestones (40 years), (**c**) Marls (8 years), (**d**–**f**) Villamalea (Castilla-La Mancha; 3, 6, and 10 years), (**g**,**h**) Mallorca (Can Coleto and Son Bordils), (**i**,**j**) A Coruña (Row 1 and Row 2), (**k**) Villena (Alicante), (**l**) Pieros (León), (**m**) Arroyo de San Serván (Badajoz), (**n**) Tobarra (Albacete), (**o**) La Rioja, (**p**) Padul (Granada), and (**q**) Leiro (Ourense).

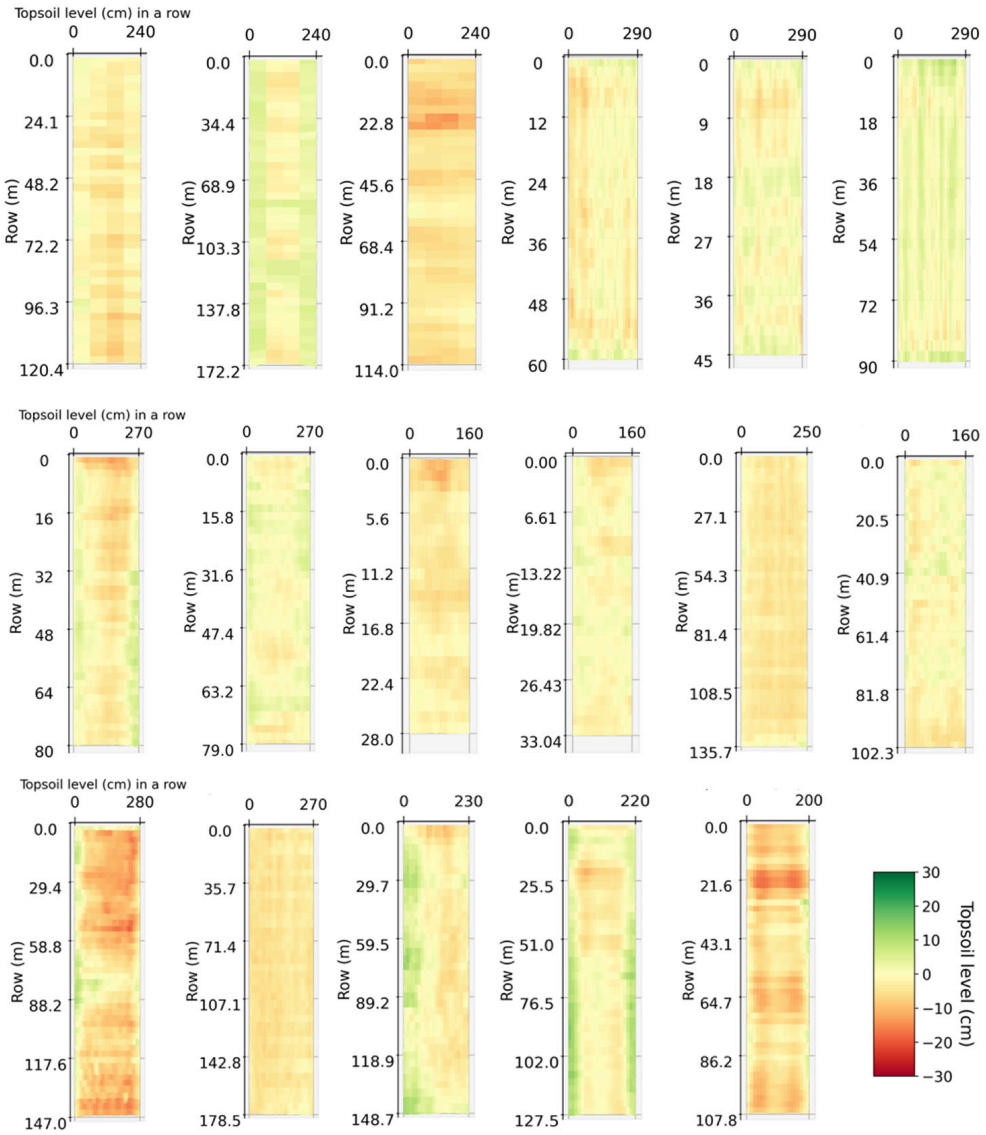


Figure 4. Spatial distribution of ISUM-derived soil surface change. The panels are ordered from (**top**) to (**bottom**) and (**left**) to (**right**) as follows: Limestones (2 years), Limestones (40 years), Marls (8 years), Villamalea (Castilla-La Mancha; 3, 6, and 10 years), Mallorca (Can Coleto and Son Bordils), A Coruña (Row 1 and Row 2), Villena (Alicante), Pieros (León), Arroyo de San Serván (Badajoz), Tobarra (Albacete), La Rioja, Padul (Granada), and Leiro (Ourense).

3.3. Variability of Soil Surface Changes Based on Boxplot Analysis

Figure 5 summarizes the variability of ISUM-derived soil surface changes using boxplots. Boxes represent the interquartile range (Q1–Q3), the central line indicates the median, and whiskers extend to the minimum and maximum values, excluding outliers. Differences in median values, dispersion, and asymmetry among sites reflect contrasting soil redistribution patterns associated with vineyard age, lithology, soil type, and management conditions. Moreover, Table 1 summarizes ISUM-derived soil erosion and deposition metrics for all study sites, including bulk density (BD), vineyard age, erosion rates expressed in tonnes per hectare per year, and descriptive statistics of soil surface change (mean, standard deviation, minimum, and maximum values). The table also allows direct comparison of soil redistribution intensity and variability among sites with different ages, lithologies, soil properties, and management practices.

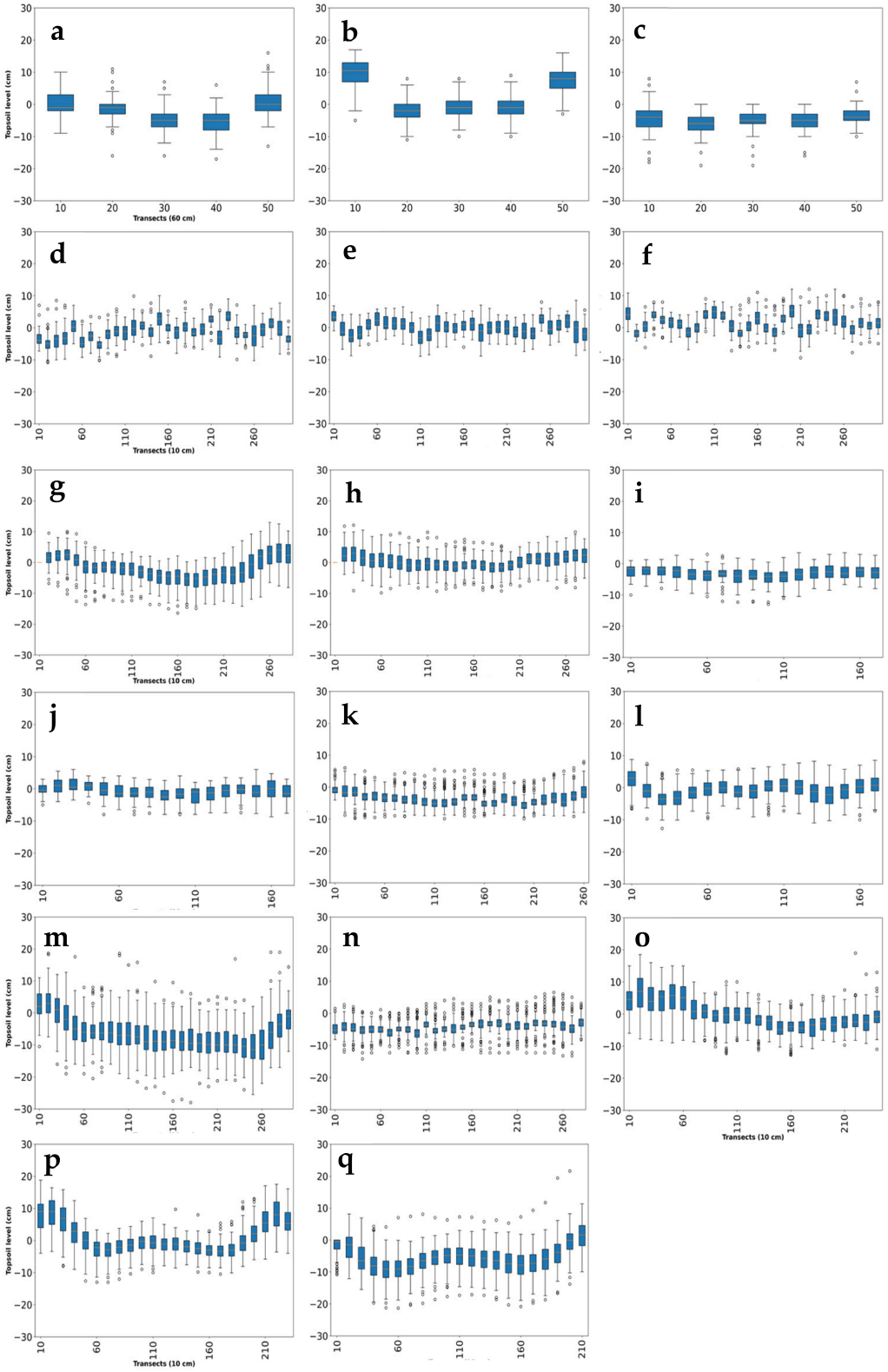


Figure 5. Distribution of ISUM values across transects and study sites. The panels are ordered from (**top**) to (**bottom**) and (**left**) to (**right**) as follows: (**a**) Limestones (2 years), (**b**) Limestones (40 years), (**c**) Marls (8 years), (**d**–**f**) Villamalea (Castilla-La Mancha; 3, 6, and 10 years), (**g**,**h**) Mallorca (Can Coleto and Son Bordils), (**i**,**j**) A Coruña (Row 1 and Row 2), (**k**) Villena (Alicante), (**l**) Pieros (León), (**m**) Arroyo de San Serván (Badajoz), (**n**) Tobarra (Albacete), (**o**) La Rioja, (**p**) Padul (Granada), and (**q**) Leiro (Ourense).

Table 1. Soil mobilization rates quantified by ISUM per experimental site.

Location	Bulk Density (g cm^{-3})	Erosion Rate (t ha^{-1} yr^{-1})	Mean (cm)	Std. Dev. (cm)	Min (cm)	Max (cm)
Limestones (2 years)	1.051	−103.2	−1.9	4.4	−17.0	16.0
Limestones (40 years)	1.054	7.2	2.7	6.1	−11.0	17.0
Marls (8 years)	1.437	−87.7	−4.9	3.5	−19.0	8.0
Villamalea (Castilla La Mancha; 3 years)	1.160	−49.9	−1.3	3.6	−10.8	10.0
Villamalea (Castilla La Mancha; 6 years)	1.140	−0.3	−0.01	3.1	−9.0	8.5
Villamalea (Castilla La Mancha; 10 years)	1.100	17.7	1.6	3.4	−9.4	12.0
Mallorca (Can Coleto)	0.770	0.9	0.3	3.1	−9.8	12.1
Mallorca (Son Bordils)	1.360	−9.8	−1.9	4.4	−14.9	13.0
A Coruña (Row 1)	1.210	−15.4	−3.2	2.3	−13.0	3.5
A Coruña (Row 2)	1.210	−3.9	−0.8	2.8	−8.7	6.0
Villena (Alicante)	1.220	−60.7	−3.5	2.6	−9.9	8.0
Pieros (León)	1.350	−5.6	−0.7	3.4	−12.7	8.8
Arroyo de San Serván (Badajoz)	1.390	−43.3	−6.2	6.3	−28.0	19.0
Tobarra (Albacete)	1.340	−62.7	−4.2	2.5	−14.2	6.5
La Rioja	1.480	−5.7	−0.3	5.1	−12.8	19.0
Padul (Granada)	1.370	17.9	0.8	5.4	−13.0	18.8
Leiro (Ourense)	1.430	−25.3	−5.8	5.	−21.3	21.6

The comparison of ISUM-derived erosion rates highlights pronounced contrasts among the studied vineyards. The highest net soil losses were recorded in young vineyards developed on unstable substrates, particularly in the limestone site (2 years; −103.3 t ha^{-1} yr^{-1}) and the marl vineyard (8 years; −87.7 t ha^{-1} yr^{-1}) in Valencia, representing the highest net soil losses observed among the studied vineyards. Similarly, high erosion rates were observed in Tobarra (−62.7 t ha^{-1} yr^{-1}), Villena (−60.7 t ha^{-1} yr^{-1}) and Villamalea (3 years; −50.0 t ha^{-1} yr^{-1}), all characterized by marked spatial variability and strongly negative mean ISUM values. In contrast, older or more stabilized vineyards showed substantially lower erosion rates or even net sediment accumulation, as observed in the limestone site (25 years; +7.2 t ha^{-1} yr^{-1}), Villamalea (10 years; +17.7 t ha^{-1} yr^{-1}) and Padul (+17.9 t ha^{-1} yr^{-1}).

Intermediate erosion intensities were found in Atlantic vineyards such as Leiro (Ourense; −25.3 t ha^{-1} yr^{-1}), A Coruña (−15.4 and −3.9 t ha^{-1} yr^{-1} for Rows 1 and 2, respectively), and Pieros (León; −5.6 t ha^{-1} yr^{-1}), where erosion rates were lower but consistently negative. Sites on Mallorca Island exhibited contrasting behaviour despite similar climatic conditions, with Can Coleto showing near-equilibrium conditions (+0.9 t ha^{-1} yr^{-1}) and Son Bordils recording moderate net erosion (−9.7 t ha^{-1} yr^{-1}). Arroyo de San Serván (Badajoz) displayed one of the highest levels of variability, combining extreme erosion (minimum −28 cm) and deposition (maximum +19 cm), resulting in a high net erosion rate (−43.3 t ha^{-1} yr^{-1}).

4. Discussion

4.1. Influence of Vineyard Age and Parent Material on Soil Redistribution

The erosion rates obtained across the studied vineyards reveal a wide range of magnitudes, confirming that soil redistribution processes in woody crops are highly sensitive to local conditions. ISUM-derived erosion rates ranged from strongly negative values, falling below −100 t ha^{-1} yr^{-1} in some young sedimentary vineyards, to positive values indicat-

ing net sediment accumulation in older or better-structured systems [41]. These gradients are consistent with the idea that vineyard age, parent material, and soil development exert a first-order control on erosion dynamics, particularly during the early stages after plantation [42]. The comparison between vineyards of contrasting ages (<10 and 10–25 years) illustrates how erosion intensity can sharply decrease as the system stabilizes, even under similar climatic conditions. In contrast, vineyards developed on fragile soils derived from marl-based or Quaternary parent materials exhibited consistently high erosion rates despite their intermediate ages, suggesting persistent vulnerability linked to soil texture, structure, and carbonate-rich parent materials [43].

The relevance of plantation age is not restricted to Mediterranean vineyards and has also been reported in other perennial systems. In commercial oil palm plantations in Malaysia, Golicz et al. [44] found lower soil organic carbon contents in immature and young mature plantations than in older plantations and suggested that younger plantations should be prioritized for soil conservation management. Although that study focused on soil organic carbon rather than erosion, it supports the broader concept that soil conditions in cropping systems evolve substantially with plantation age. Similarly, Sun et al. [45] reported lower runoff and soil erosion in mature plantations than in young plantations in southern China, indicating that the progressive development of vegetation, litter, and soil surface conditions can enhance soil and water conservation as plantations mature. Together with previous vineyard-specific evidence [40], these findings suggest that plantation age should be considered when designing and timing soil conservation measures in perennial agricultural systems.

The impact of parent material on soil erosion rates is amplified in bare and intensively ploughed vineyard soils. Previous studies on the impact of parent material on soil erosion have demonstrated that marls are highly erodible, but soil losses are low once vegetation cover is high [46,47]. Lithology and soil type clearly emerge as key drivers of the observed spatial patterns. Vineyards developed on marls and fine-textured substrates showed the highest net soil losses, reflecting their low aggregate stability and high susceptibility to surface sealing and runoff generation. Conversely, limestone-derived soils, although initially prone to erosion after planting, tended to exhibit lower long-term erosion rates as soil structure improved and sediment redistribution became more balanced [48,49]. These results align with previous studies highlighting the role of parent material in controlling erosion processes in Mediterranean agroecosystems, but the present dataset offers a unique field-based comparison under standardized measurement conditions [37]. Importantly, the observed differences cannot be attributed solely to slope or climate, as several vineyards with comparable topographic settings displayed markedly different erosion signals depending on their lithological context.

4.2. Management and Topographic Controls on Erosion–Deposition Patterns

Management practices also play a relevant, though more complex, role in explaining the observed erosion patterns. Vineyards under conventional tillage, especially those recently established, generally showed higher erosion rates than older systems or those with partial residue retention [50–52]. However, the influence of management is not always straightforward, as its effects interact with soil properties, vineyard age, and historical land use [53]. In some cases, vineyards with similar management practices displayed contrasting erosion responses, suggesting that management alone cannot offset the inherent vulnerability imposed by soil type and parent material. This highlights the need to interpret erosion rates as the result of multiple interacting controls rather than as the outcome of a single dominant factor.

Topography represents an additional control on the spatial organization of erosion and deposition within vineyards. Both slope gradient and hillslope position can influence runoff generation, sediment transport capacity, and soil redistribution within the field. Vineyards located in upper-slope or headwater positions are mainly affected by locally generated runoff and sediment transport, whereas vineyards situated in mid- or lower-slope positions may additionally receive water and sediment from upslope contributing areas. These external inputs can favour local deposition or, alternatively, enhance erosion where concentrated flow paths develop [54,55].

The influence of slope should therefore not be interpreted independently of hydrological connectivity and field boundary conditions. Vineyards with similar slope gradients may exhibit markedly different erosion–deposition patterns depending on whether runoff and sediment can enter from adjacent plots, tracks, or natural slopes, or whether physical barriers restrict these external inputs. Consequently, ISUM-derived soil surface changes should be interpreted within the topographic and hydrological context of each vineyard.

Under such conditions, the measured erosion patterns can be more confidently attributed to internal processes within the vineyard itself. Conversely, in vineyards lacking physical barriers or located in downslope or piedmont positions, part of the measured soil accumulation may reflect external sediment contributions, while erosion hotspots may be amplified by concentrated flow paths connecting upslope areas, as observed on Mallorca Island or in Castilla-La Mancha. These differences show that similar slope gradients do not necessarily imply comparable erosion responses when the connectivity structure of the system differs. Although a full quantification of hydrological connectivity was beyond the scope of this study, the results underline the need to interpret ISUM measurements within their geomorphological and hydrological context, particularly when comparing sites in contrasting landscape positions. Future studies combining ISUM with detailed topographic analyses, runoff tracing, or high-resolution DEMs could further disentangle the relative roles of slope position, connectivity, and soil management in controlling soil redistribution at the field scale [56,57].

4.3. Cross-Site Comparability and Uncertainty of ISUM-Derived Soil Mobilization Rates

The standardized application of ISUM and the use of a common calculation procedure allow soil mobilization rates to be compared consistently among the studied vineyards. However, these comparisons should be interpreted with caution because the sites differ markedly in vineyard age, slope gradient, lithology, soil properties, climatic conditions, management practices, and hillslope position. Consequently, the reported rates represent site-specific, long-term net soil redistribution under contrasting environmental settings rather than directly comparable erosion responses obtained under controlled conditions. Cross-site comparisons are therefore most appropriate for identifying broad contrasts and recurring patterns, while the independent contribution of individual controlling factors cannot be fully isolated using the present observational design.

Several sources of uncertainty should be considered when interpreting ISUM-derived soil surface changes and annualized soil mobilization rates. First, ISUM assumes that the graft union or stump reference provides a stable indicator of the original soil surface position. However, small differences in graft-union height among individual vines, variability in original planting depth, or local disturbances around the vine stock may introduce uncertainty into individual measurements. Second, the timing of field surveys may influence the measured surface level because soil moisture conditions, recent tillage, and temporary surface roughness can modify local microtopography. To minimize these effects, measurements were avoided immediately after intense rainfall events or recent tillage operations, surface conditions were visually inspected, and anomalous observations were documented

during field surveys. Nevertheless, residual differences among sites cannot be completely excluded. Third, the conversion of surface change into mass-based soil mobilization rates depends on measured bulk density and the reference period or vineyard age used for annualization. Consequently, the reported values should be interpreted as long-term average net soil redistribution rates over the corresponding reference period rather than as directly measured annual erosion rates. These sources of uncertainty are particularly relevant when comparing vineyards with contrasting ages and environmental conditions and should therefore be considered alongside the standardized sampling protocol.

4.4. Methodological Strengths, Limitations, and Future Research

From a methodological perspective, one of the main strengths of this study lies in the standardized application of ISUM across multiple sites and environmental contexts. Unlike previous studies based on rainfall simulations, plot-scale measurements, or meta-analyses compiling heterogeneous datasets, this study relies on direct field measurements obtained by the same research group using a consistent protocol and processed following identical analytical procedures [25]. This approach minimizes methodological bias and enhances comparability among sites, allowing robust regional-scale interpretations. The resulting dataset represents, to our knowledge, the most extensive field-based application of ISUM in vineyards and other cultivated systems to date. Another methodological advantage concerns the spatial representation of erosion patterns. The erosion maps presented in this study are based on direct measurements without spatial interpolation, meaning that each pixel corresponds to an actual field observation rather than a modelled or smoothed value. This contrasts with other ISUM-based studies where interpolation methods can substantially alter the perceived spatial structure of erosion and deposition. By preserving the raw spatial signal, the maps provide a more realistic depiction of soil redistribution processes and allow the identification of sharp local contrasts that might otherwise be masked. This pixel-by-pixel approach strengthens the interpretability of the results, particularly when linking erosion patterns to microtopography, vineyard layout, and management features.

Despite these strengths, several limitations must also be acknowledged. Although the thirteen vineyard sites encompass a broad range of climatic, lithological, topographic, and management conditions, they cannot represent the full diversity of viticultural systems across Spain. The relatively limited number of sites and the observational nature of the study also restrict the ability to statistically isolate the independent effects of vineyard age, lithology, climate, topography, and management. Furthermore, complete soil-property datasets were not available for all vineyards, limiting a more detailed assessment of the influence of texture, organic matter, and other soil characteristics on the observed redistribution patterns. The absence of high-resolution topographic information, such as UAV-derived DEMs, for all sites also prevents a detailed quantification of flow pathways and sediment connectivity. Future research should therefore expand the number of monitored vineyards and incorporate repeated ISUM surveys over time to distinguish persistent redistribution patterns from shorter-term surface changes. Combining ISUM with high-resolution UAV-derived topography, runoff and sediment monitoring, erosion plots, and complementary modelling approaches would allow a more detailed assessment of the interactions among slope, hydrological connectivity, soil properties, and management. Such integrated approaches would also improve the attribution of observed erosion–deposition patterns to individual controlling factors and strengthen the transferability of multi-site comparisons to broader vineyard regions [58,59].

Soil moisture conditions and recent tillage may also introduce uncertainty into ISUM measurements because both factors can temporarily modify soil roughness, aggregation, and the local position of the soil surface. Although field conditions were visually inspected and anomalous or disturbed surface conditions were documented during the surveys, these short-term effects cannot be completely excluded. Their influence is expected to be most relevant for individual measurements rather than for the overall spatial patterns derived from the large number of observations collected within each vineyard.

This study highlights both the potential and the challenges of conducting large-scale, field-based erosion assessments in perennial cropping systems. The findings provide a solid empirical basis for future methodological integration and for more harmonized, multi-site assessments of soil erosion in these systems. One of the main challenges lies in achieving full temporal and methodological synchronization across sites, as fully parallel measurements would require substantial logistical coordination, economic resources, and personnel availability. Future research should therefore focus on combining ISUM with other quantitative approaches, including erosion plots, modelling frameworks other than RUSLE, and repeated measurements over time, to capture both short-term dynamics and long-term trends. Such multi-method assessments could support both scientific understanding and the development of effective soil conservation strategies in vineyards under changing environmental and management conditions.

5. Conclusions

This study provides a unique field-based comparison of soil erosion rates and spatial redistribution patterns across thirteen vineyards under contrasting environmental and management conditions in Spain. By applying the Improved Stock Unearthing Method (ISUM) using a standardized protocol, we were able to quantify erosion and deposition processes consistently across multiple sites, lithologies, vineyard ages, and management regimes. The results reveal a wide range of erosion rates, from severe soil losses below -100 t ha^{-1} yr^{-1} in young vineyards developed on limestone or marls to moderate erosion or even net sediment accumulation in older or more stable systems. Vineyard age and parent material emerged as primary controls on erosion magnitude, while management practices modulated, but did not fully override, the influence of soil type and lithology. Marl-derived soils consistently showed high vulnerability to erosion, whereas limestone-derived soils exhibited a marked decrease in erosion rates with time since planting. The spatially explicit erosion maps, based exclusively on measured values without interpolation, highlight strong intra-plot variability and sharp contrasts between erosion and deposition zones. This pixel-level representation provides a realistic depiction of soil redistribution processes and avoids artefacts commonly associated with interpolation-based mapping approaches. The combination of volumetric calculations, conversion to mass-based erosion rates, and statistical analysis reinforces the robustness of ISUM as a quantitative tool for vineyard erosion assessment. Despite acknowledged limitations related to temporal synchronization, soil-property availability, and ancillary topographic data, this study demonstrates that ISUM can be successfully applied at regional scales to generate comparable erosion datasets. The results underscore the need for early soil conservation measures in newly planted vineyards and support the integration of standardized field-based erosion measurements into broader and emerging European soil monitoring frameworks.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrology13090251/s1, Table S1: Main environmental characteristics of the study areas; Table S2: Main morphological characteristics of the plantation framework and land management strategies.

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