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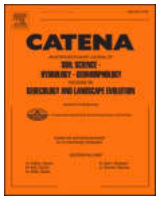

Evaluating the effectiveness of four representative land uses in soil and water conservation on a typical rainfed Mediterranean agricultural landscape in La Rioja (Spain)

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ABSTRACT

Mediterranean steep-slope agricultural landscapes are highly vulnerable to soil erosion, exacerbated by climate and land use changes. In Spain, the 1992 EU Common Agricultural Policy reform led to an increase in tilled, unseeded fallow land, altering soil erosion dynamics. However, systematic research comparing the hydrological and soil conservation performance of fallow land versus traditional crops remains limited.

This study addresses this gap by evaluating the hydrological and sedimentary responses of tilled, unseeded fallow land compared to three representative Mediterranean crops—olive, vineyard, and barley—on steep slopes in La Rioja, Spain. We propose a flexible modelling approach (SIMulated Water Erosion model; SMIWE) to determine suitable land use for steep-slope agriculture in the region by simulating water and soil movement during extreme rainfall, which is expected to become more frequent due to climate change.

The analysis examines and compares differences in hydro-sedimentary outputs, including surface water depth, sediment flux, and erosion rates. Results show that fallow land had the lowest surface water depth 0.001 m, but the highest sediment flux 0.04 kg m^{-1} s^{-1} and erosion rate (39 % higher than vineyards). Among cultivated lands, vineyards had the lowest sediment flux and erosion rates, with 13 % lower than olive and 2 % lower than barley fields. Total erosion in fallow land was significantly higher than in other land uses, followed by olive, barley, and vineyards. Despite the uncertainty and the limitations of the modelling exercise, these findings highlight the vulnerability of unseeded fallow land to soil erosion and underscore the importance of crop selection and management strategies for improving landscape resilience and sustainability.

1. Introduction

Mountain and steep-slope agriculture played a significant role in Europe due to the multiple roles they play in agronomy, culture, and tradition, as represented by ancient agricultural systems. However, water and soil loss in hilly and mountainous cultivation systems is under pressing concern (Arnaez et al., 2011; Durán Zuazo et al., 2006; García-Orenes et al., 2009; García-Ruiz, 2010; Khorchani et al., 2020; Lasanta et al., 2001; Nadal-Romero et al., 2018). In Spain, soil erosion is a major concern and contributes to almost 20 % of the total soil erosion in Europe (Panagos et al., 2015b). The dominance of cereal crops, vineyards, and olive orchards also contributes to various forms of soil erosion, particularly on steep-slope agriculture (Gómez et al., 2014; Nadal-Romero and García-Ruiz, 2025). For example, between the 16th and 19th centuries, extensive cereal farming resulted in widespread soil degradation. In addition, the growth of vineyards and olive orchards in steep-slopes has increased their vulnerability to soil erosion, particularly during extreme storm events (García-Ruiz, 2010).

The increasing frequency of high-intensity rainfall due to climate change exacerbates the challenge of soil erosion in hilly and mountainous cultivation systems (Pijl et al., 2022). Numerous studies reported a paradoxical increase in Mediterranean extreme daily rainfall despite an overall decrease in total annual precipitation (Myhre et al., 2019; Panagos et al., 2021; Ribes et al., 2019; Zittis et al., 2021). For instance, in the French Mediterranean area, the frequency of daily rainfall exceeding 200 mm/day has quadrupled compared to previous

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records from 1961 to 2015 (Ribes et al., 2019), and similar trends have been observed in the Spanish Mediterranean coast (Miró et al., 2022). The water erosion-induced soil loss is projected to increase by up to 22.5 % as a result of the anticipated rise in future rainfall erosivity (Panagos et al., 2021). The resultant slope failures, such as gully erosion, landslides, debris flows, or terrace failure, are therefore more prevalent, particularly after land abandonment (Tarolli et al., 2021).

However, land use and land cover (LULC) is considered the most critical factor in the evaluation of water and soil degradation, often surpassing the impact of rainfall intensity and slope steepness (Renard, 1997; Rodriguez-Lloveras et al., 2016). Different types of LULCs result in distinct patterns of hydrological connectivity and surface runoff (Llena et al., 2024), conditioning sediment transport and shaping erosion processes (Feldmann et al., 2023). Spain experienced huge LULC changes in 1992, when the European Union (EU) launched the Common Agricultural Policy (CAP) reform, which required farmers to set aside a portion of arable land as fallow. This led to a substantial increase in fallow areas across Spain (Boellstorff and Benito, 2005). There are two kinds of fallow lands: tilled unseeded fallow land, mainly located in semiarid regions, and seeded fallow, more common in humid temperate areas (García-Ruiz and Lana-Renault, 2011). Both practices aim to improve soil water humidity and fertility. Long fallowing (16–18 months) practices remain widely distributed in cereal-growing areas and occupy half of the rainfed agriculture of Spain (Moret et al., 2006; Recuero et al., 2019). Although the fallow policy was adopted to meet the environmental requirements, several studies have highlighted that fallow exacerbated the soil degradation and land abandonment process (García-Ruiz, 2010; Lasanta et al., 2017; van Leeuwen et al., 2019). For example, Boellstorff and Benito (2005) monitored the soil erosion risk before the CAP reform policy using the RUSLE model. The findings of this study indicated that the CAP reform policy triggered a significant rise in soil loss in the mountain agriculture of Torrijos (Spain). The authors also demonstrated that unseeded fallow has a higher risk of soil erosion, at least double that of seeded fallow based on one-year field data in the mountain agriculture of central Spain (Boellstorff and Benito, 2005).

Cultivation in steep-slopes and mountainous areas makes soil and water conservation more complex, leading to a variety of erosive processes that vary across spatio-temporal scales and are difficult for the scientific community to predict (García-Ruiz, 2010; Pijl et al., 2022). Effective erosion control requires site-specific management strategies (Larson et al., 1983), since LULC, along with management practices such as crop selection and tillage methods, strongly influence soil erosion rates (García-Ruiz, 2010; Panagos et al., 2015a). Previous studies have shown positive correlations between LULC and surface runoff and soil loss, assuming constant slope length and gradient (Maetens et al., 2012). However, identifying the most sustainable LULC configuration for Mediterranean rainfed landscapes, especially in terms of water and soil dynamics between cultivated land and fallow, remains a topic of ongoing debate. Field-based assessments have been widely applied to study erosion dynamics and provide valuable insights. However, they face several constraints in addressing the complexity of these processes. Monitoring extreme rainfall events requires long-term data collection, which is often resource-intensive and impractical. Additionally, field study findings are highly site-specific, making it difficult to apply results to broader regions with different environmental conditions. Moreover, such assessments are limited by current climate conditions and cannot easily incorporate future projections. Therefore, despite its limitations, a modelling approach could be a robust alternative in providing a systematic and flexible framework for understanding water and soil erosion processes under varying rainfall scenarios. Its ease of replication in different environmental settings makes it a valuable tool for guiding sustainable land management decisions.

For these reasons, this research aims to investigate the hydrological and soil erosion processes response to extreme rainfall events by a physically-distributed model SIMWE (SIMulated Water Erosion model) among different LULCs in the steep-slope agricultural landscape of La Rioja, Spain. It compares no-seed fallow lands with three representative crop types (olive, vineyard, and barley) with similar slope conditions. Specifically, the study's objectives are: (1) to simulate water and soil erosion conditions using the physically-distributed model SIMWE (SIMulated Water Erosion model), including water depth of surface water, sediment flux, sediment concentration, and erosion and deposition under an extreme rainfall scenario (101.6 mm h^{-1}; 2023) and LULCs conditions; (2) to analyze and compare the differences in hydro-sedimentary outputs of the model, including surface water depth, sediment flux, sediment concentration, and erosion–deposition rates among the four LULCs; and (3) to identify the most suitable LULC and crop types for steep-slope agriculture (without terracing) in La Rioja, based on their water and soil conservation functions. We hypothesize that different LULCs exhibit distinct hydrological and sedimentation processes, with fallow land being more susceptible to water and soil loss compared to other LULC categories. Despite the uncertainties, this study could provide valuable insights into the suitability of various cropland configurations in steep-slope agriculture within Mediterranean landscapes and offer guidelines for effective land management in the face of climate change.

2. Methods

2.1. Study area

The research was carried out in three agricultural areas of the upper part of the Ebro Valley, within the La Rioja Region (North Spain). The elevation of the study area ranges between 400–600 m a.s.l, with a mean slope of 8°. The experimental field crops are located on glacis and contact levels between glacis in the Iregua River (Sites 2 and 3) and the Jubera River (Site 1) (Gonzalo Moreno, 1981), both of them tributaries of the Ebro River on its right bank after passing through the city of Logroño (Fig. 1). The dominant lithology consists of clays and silts alternating with sandstones and sandy limestones in thin layers (Miocene), and the presence of terraces and glacis from the Quaternary. The soil texture is mainly composed by is silty loam, with percentages of clay between 13 and 21 %, silt 57–59 %, and sand about 20–30 %, and low organic matter content. Annual precipitation is around 405 mm, with over 60 % of rainfall occurring in spring and autumn, while summer and winter are the dry seasons. However, heavy and intense rainfall storms can occur in summer and the beginning of autumn, being considered extreme events that can modify rainfall patterns. The average temperature is 13.9 °C (period 1981–2010, Logroño airport meteorological station, AEMET; Fig. 1). The main LULC are Mediterranean rainfed crops, mainly composed of cereal crops, olive trees, and vineyards (Fig. 2). Shrubs and bushes composed of *Genista scorpius*, *Thymus vulgaris,* and *Salvia rosmarinus* appear in small areas where agricultural cultivation is not possible, due mainly to the rocky outcrop or the high slope, while orchards and irrigated crops appear near the valley bottoms.

2.2. Experimental site selection

There are 3 experimental sites in total, each with four types of LULC, resulting in a total of 12 study plots (Fig. 1). The selection of study plots followed specific criteria to ensure homogeneity in terms of slope gradient, soil type, vegetation cover, climate, and land use history. 12 plots in total were selected in reference to the field survey, with each site having 4 LULCs, including 3 kinds of crop types (olive, vineyard, barley) and tilled, unseeded fallow land (Fig. 2). The criteria used for selecting the study plots were as follows: (1) All study plots were located at approximately the same elevation (between 400–600 m a.s.l.), slope gradient (around 7–12°), and soil texture (silty loam); (2) Uniform cultivation practices were observed across all the cropland plots, with no presence of grassland cover within the fields (Fig. 2); (3) The orientation

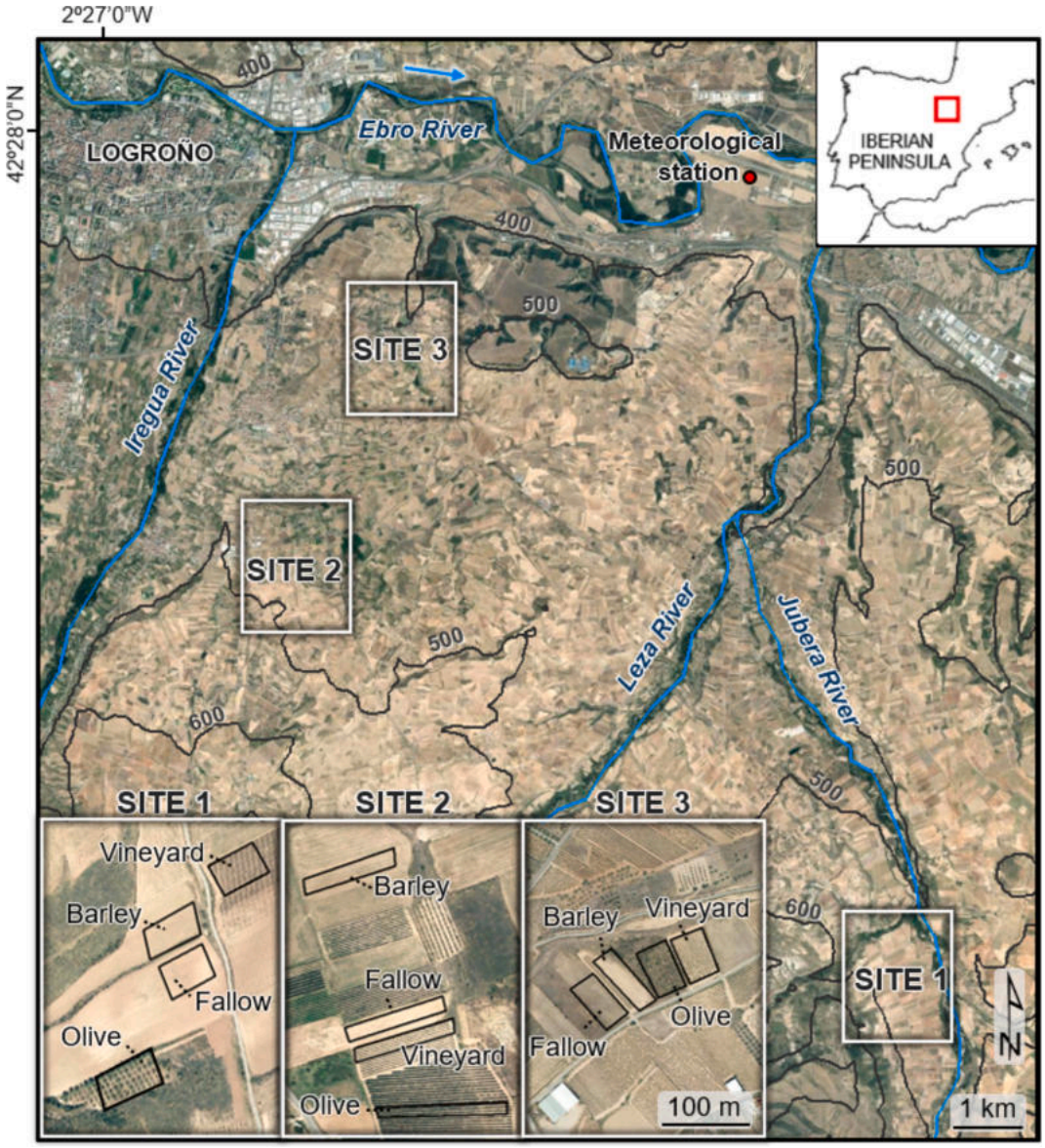

Fig. 1. Location of the experimental sites with their corresponding study plots within the context of the Iberian Peninsula. Note that the equidistance between contour lines is 100 m.

of plants within the study areas was parallel to the slope; (4) All the fallow plots were in the same tillage practice: subsoiling tillage; (5) The mean area of each study plot was 0.21 ha. These rigorous criteria ensured that the selected study areas shared similar characteristics and minimized potential confounding factors, allowing for more accurate comparisons and evaluation of water and soil conservation effectiveness among different cropland types on steep-slopes.

2.3. Modelling surface runoff and sediment transport

For the evaluation of soil and water loss, a modelling approach was combined with field data collection to achieve the research objectives. The SIMWE (SIMulated Water Erosion model) was applied to provide detailed information on the hydrological process and sediment transport (Fernandes et al., 2017; Mitas and Mitasova, 1998; Pijl et al., 2022). The modules of SIMWE include 'r.sim.water' and 'r.sim.sediment' (Mitas and Mitasova, 1998). The former focuses on the simulation of water depth (m) of the overland flow and the latter concentrates on the simulation of sediment concentration (particles m^{-3}), and the process of soil erosion rate (Kg m^{-2} s^{-1}) and soil deposition rate (Kg m^{-2} s^{-1}) (Mitas and Mitasova, 1998). For the r.water module, the input parameter needs a digital terrain model (DTM), infiltration rate (mm h^{-1}), and Manning's coefficient. The output result includes the water depth of the overland flow and water discharge. In the module of 'r.sim.sediment', the input data including DTM (0.5 m), manning's coefficient, water depth of the overland flow, transport capacity coefficient (s),and critical shear stress (Pa) as well as detachment capacity (s m^{-1}). The output data includes sediment flux (Kg m^{-1} s^{-1}), sediment concentration (particles m^{-3}), soil erosion rate (Kg m^{-2} s^{-1}), and soil deposition rate (Kg m^{-2} s^{-1}) maps. The advantage of SIMWE is that allows for a more detailed analysis in capturing nuances in flow direction during the hydrologic and sediment transport process (Koco, 2011). The input parameters for the model are listed in Table 1. The DTM was derived from a LiDAR-point cloud surveyed in 2016 by the Spanish National Geographic Institute (PNOA-CNIG), which had a spatial resolution of 1.25 points m^{-2} and an estimated root mean square error (RMSE) of 0.25 m, allowing to depict of most of the microrelief variations. For this study, the maximum precipitation intensity (101.6 mm h^{-1}) was selected for simulating the extreme rainfall scenario due to two reasons: (1) this was the highest rainfall intensity observed at the Leza meteorological station on June 21,

Fig. 2. Four representative land use and land cover types were selected for this study: (a) olive trees, (b) vineyard, (c) tilled, unseeded fallow land, and (d) barley. The photos were taken by Wendi Wang in June 2023.

Table 1
The input parameters for the SIMulated Water Erosion (SIMWE) model.

Crop type	Rainfall intensity [mm h^{-1}]	Soil infiltration [mm h^{-1}]	Manning's roughness Coefficient	Detachment capacity [s m^{-1}]	Sediment transport capacity [s]	Critical shear stress [Pa]
Barley (1)	101.6	76.8	0.14	0.003	0.0003	0.5
Fallow (1)	101.6	73.2	0.02	0.03	0.03	0.5
Olive (1)	101.6	41.4	0.15	0.003	0.0003	0.5
Vineyard (1)	101.6	77.4	0.1	0.003	0.0003	0.5
Barley (2)	101.6	43.2	0.14	0.003	0.0003	0.5
Fallow (2)	101.6	101.4	0.02	0.03	0.03	0.5
Olive (2)	101.6	39.6	0.15	0.003	0.0003	0.5
Vineyard (2)	101.6	71.4	0.1	0.003	0.0003	0.5
Barley (3)	101.6	54	0.14	0.003	0.0003	0.5
Fallow (3)	101.6	54.6	0.02	0.03	0.03	0.5
Olive (3)	101.6	43.2	0.15	0.003	0.0003	0.5
Vineyard (3)	101.6	26.4	0.1	0.003	0.0003	0.5

Note: In the table, the number in the "()" denotes different experimental sites. For instance, Barley (1) means the barley in the site 1.

2023, and (2) although most rainfall in the region occurs in spring and autumn (see Section 2.1), intense summer events tend to cause severe erosion, making it a critical season for assessing extreme impacts (see section 2.1). Two rounds of field surveys were conducted. On June 30, 2023, three experimental sites (12 field plots) were selected. The infiltration rates were measured from July 19 to July 26, 2023, in the second field survey by using a Mini Disk infiltrometer. The manning coefficient was selected based on a literature review in similar LULC classes (Pijl et al., 2020; Romero et al., 2007; Ullrich and Volk, 2009). The other input parameters including detachment capacity (s m^{-1}), sediment transport capacity (s), and critical shear stress (Pa) were set according to the application of the model developer (Mitas and Mitasova, 1998; Neteler and Mitasova, 2002).

2.4. Statistical analysis

The Kruskal-Wallis test was applied to compare the results among different LULCs to determine the statistical significance. Dunn's test was subsequently conducted to determine specific LULC data pairs with significant differences. Bootstrap analysis was utilized to estimate confidence intervals for the result for each LULC, and to understand the precision and stability of the median values through the 95 % confidence intervals. All the statistical tests were conducted by RStudio.

3. Results

3.1. Spatial distribution of runoff and sediment transport

The general water and soil patterns were represented by the output of the model by water depth (m) of surface runoff (Fig. 3), sediment flux

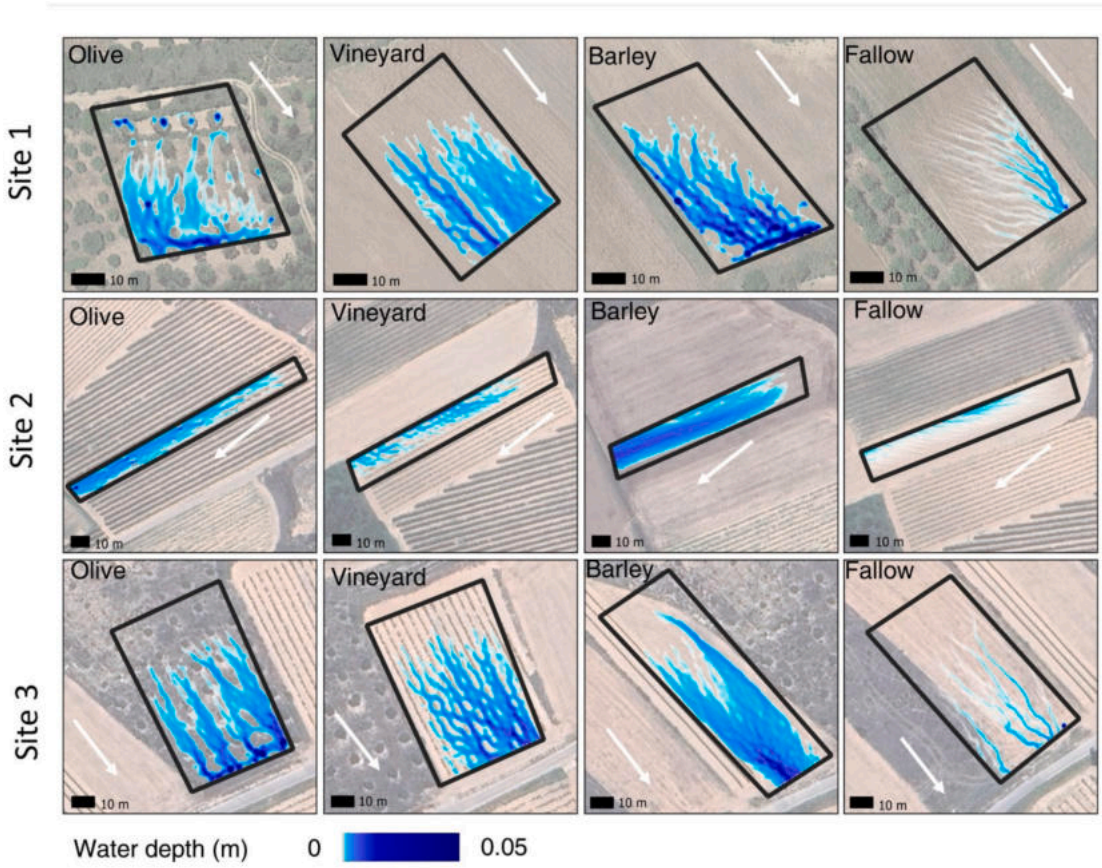

Fig. 3. Spatial distribution of the modelled surface runoff for each of the land use and land cover classes of the 3 experimental sites (the white arrow on each map indicates the direction of the slope).

(Kg m^{-1} s^{-1}) (Fig. 4), sediment concentration (particles m^{-3}) (Fig. 5), and the erosion and deposition process (Kg m^{-2} s^{-1}) (Fig. 6). All these parameters were modelled for the 4 different LULC classes (i.e., olive groves, vineyards, barley fields, and fallow lands) at 12 plots based on the SIMWE simulation. As depicted, the water depth (Fig. 3) ranges from 0 to 0.05 m during a rainfall event of 101.6 mm/hour over a 15-minute interval, based on the maximum recorded rainfall event at Leza Station on June 21, 2023. Fig. 2 clearly illustrates that overflow runoff in fallow lands is significantly less compared to other types of croplands, with site 2 showing minimal visible runoff in the fallow areas. The barley exhibits a more concentrated runoff pattern, whereas the olive grove and vineyard experience more dispersed runoff.

Fig. 4 displays the rate of sediment flux (Kg m^{-1} s^{-1}). The tilled, unseeded fallow land is the highest among all the LULCs, especially at site 2. Compared to the other two locations, barley at site 3 has the lowest sediment flux. The sediment flux ranges from 0 to 0.23 Kg m^{-1} s^{-1} across the study area. Overall, sediment distribution patterns are decentralized in olive groves and vineyards, aligning with the inter-row spacing, whereas the distribution is more centralized in barley fields and fallow lands. The sediment distribution pathway is not consistent with the runoff pathway in Fig. 3.

Fig. 5 presents the sediment concentration (particles m^{-3}) among different LULCs. Olive groves and barley fields show relatively higher sediment concentrations in the downslope areas, especially at Site 1. Fallow lands exhibit relatively lower sediment concentrations, as indicated by the lighter colors on the map. Olive and barley fields exhibit quite high value, followed by vineyards. Sediment concentrations range from 0 to 0.83 particles m^{-3}. In terms of distribution patterns, the pathway of sediment concentrations, surface runoff, and sediment flux is visibly distinct.

Fig. 6 presents an analysis of the erosion (values less than 0) and deposition (values greater than 0) processes, with a range from −0.4 to 0.4 Kg m^{-2} s^{-1}. The maps illustrate that erosion and deposition processes often occur sequentially. In Site 1, all types of croplands exhibit relatively more intensive erosion and deposition activities. Specifically, in the olive groves at Site 1, erosion and deposition are prominently observed on the downhill side of the plots. In the barley fields, it appears that the amount of eroded sediment exceeds the deposited sediment in the downhill direction of the study area. At sites 2 and 3, all crop types experience significant erosion and deposition processes along the slopes, not confined to the downslope areas. Site 2 demonstrates minimal erosion processes.

3.2. Differences between various LULCs in water depth, sediment flux, sediment concentration, erosion, and deposition

Fig. 7 presents the density plots for water depth, sediment concentration, sediment flux, and erosion–deposition. In the water depth density plot (Fig. 7), the primary peaks for barley fields, fallow lands, olive groves, and vineyards are observed at specific values. The distribution pattern for fallow lands is more concentrated, as indicated by the narrower shape of the curve, whereas the other croplands exhibit a more dispersed distribution. The median value for each LULC is approximately barley: 0.005 m, fallow: 0.001 m, olive: 0.006 m, and vineyard: 0.005 m, with fallow lands showing significantly lower values compared to other croplands. The water depth data for all croplands display a single peak. Kruskal-Wallis test showed significance (p-value < 0.05), indicating that water depth is significantly different among all crop types. Following the significant Kruskal-Wallis test, Dunn's test was conducted for post-hoc multiple comparisons. The results showed water

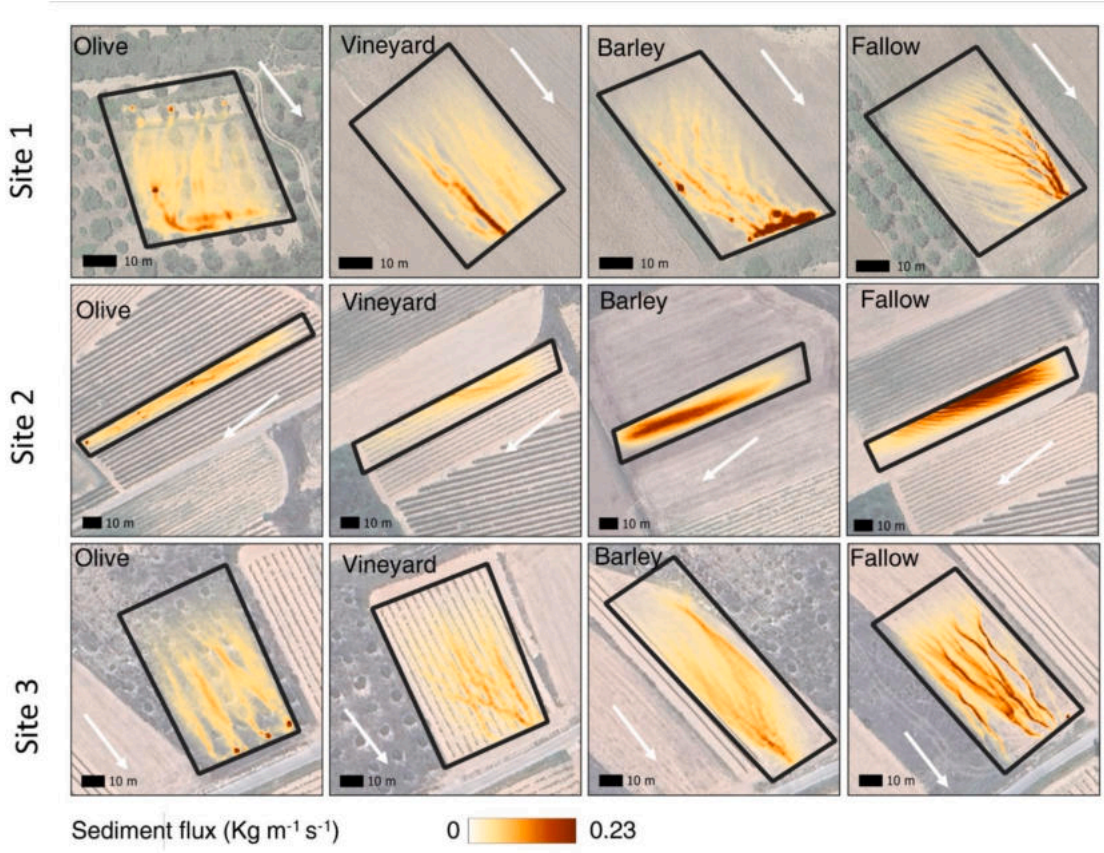

Fig. 4. Spatial distribution of sediment flux for each of the land use and land cover classes in the 3 experimental sites (the white arrow on each map indicates the direction of the slope).

depth of fallow land is significantly different from other LULCs (all p-values < 0.05).

For sediment concentration, barley fields show a primary peak, indicating that a concentration around 0.45 particles m^{-3} is most frequent, with a median value of approximately 0.5 particles m^{-3}. Fallow lands display two prominent peaks, indicating high frequencies at two different concentration ranges: around 0.2 particles m^{-3} and 0.4 particles m^{-3}, with a median value at approximately 0.3 particles m^{-3}. Olive groves exhibit a pronounced increase between 0.4 particles m^{-3} and 0.7 particles m^{-3}, indicating a more frequent distribution within this range, with the median at around 0.5. Vineyards exhibit peaks between 0.3 particles m^{-3} and 0.5 particles m^{-3}, indicating higher frequencies in this concentration range, with the median data at around 0.35 particles m^{-3}. The sediment concentration in fallow lands is significantly lower than that in other types of croplands. Statistic tests revealed significant differences among all the LULCs, except for olive and barley.

The density plot for sediment flux effectively visualizes the distribution of sediment flux across different LULCs and reveals a comparable distribution across all croplands except olive (Fig. 7). Olive shows a different distribution, with a notable peak at a higher sediment flux compared to the others. Vineyards and olive groves exhibit two main peaks around specific values, indicating higher frequencies in this range. The median values for vineyards and olive groves are 0.02 Kg m^{-1} s^{-1} and 0.03 Kg m^{-1} s^{-1}. Barley fields and fallow lands display a primary peak focused on particular values, with median values of 0.03 Kg m^{-1} s^{-1} and 0.04 Kg m^{-1} s^{-1}, respectively. Overall, vineyards have the lowest sediment flux values, whereas fallow lands exhibit the highest values. Dunn's test confirms that these differences are statistically significant (all p-values < 0.05). The density plot shows that the erosion–deposition values for all four types are heavily centered around 0, indicating overall changes in erosion and deposition counterbalance one another. The median values for barley, fallow, olive, and vineyard are -0.00154 Kg m^{-2} s^{-1}, -0.00220 Kg m^{-2} s^{-1}, -0.00166 Kg m^{-2} s^{-1}, and -0.00142 Kg m^{-2} s^{-1}. Compared to the vineyard, the total erosion value of other LULCs is 39 % higher for fallow, 13 % higher for olive, and 2 % higher for barley.

Fig. 8 shows the results of the bootstrapping analysis at a 95 % confidence level, used to further investigate the variability and reliability of model simulations across different investigated parameters. For water depth, barley presents the highest median value and fallow the lowest, confirming the statistical significance of these differences through non-overlapping confidence intervals. In terms of sediment concentration, olive and barley fields show higher median values compared to other LULCs. On the other hand, fallow shows higher median values of sediment flux. Higher erosion rates for fallow are also evident in the erosion–deposition analysis, indicating significant soil vulnerability of fallow during extreme rainfall events.

4. Discussion

4.1. Influence of different LULCs in surface runoff and soil loss control

The impact of LULCs on soil erosion remains contentious across studies (Maetens et al., 2012; García-Ruiz et al., 2013, García-Ruiz et al., 2015). Our results indicate that sediment flux in fallow and barley fields is higher compared to olive groves and vineyards, which is consistent with some of the previous findings. For instance, Nadal-Romero et al. (2013) concluded that cereal farming on steep-slopes poses a significant issue for soil management in Mediterranean mountain areas (Nadal-Romero et al., 2013). This accounts for the widespread occurrence of degraded slopes that are characterized by various erosion in the

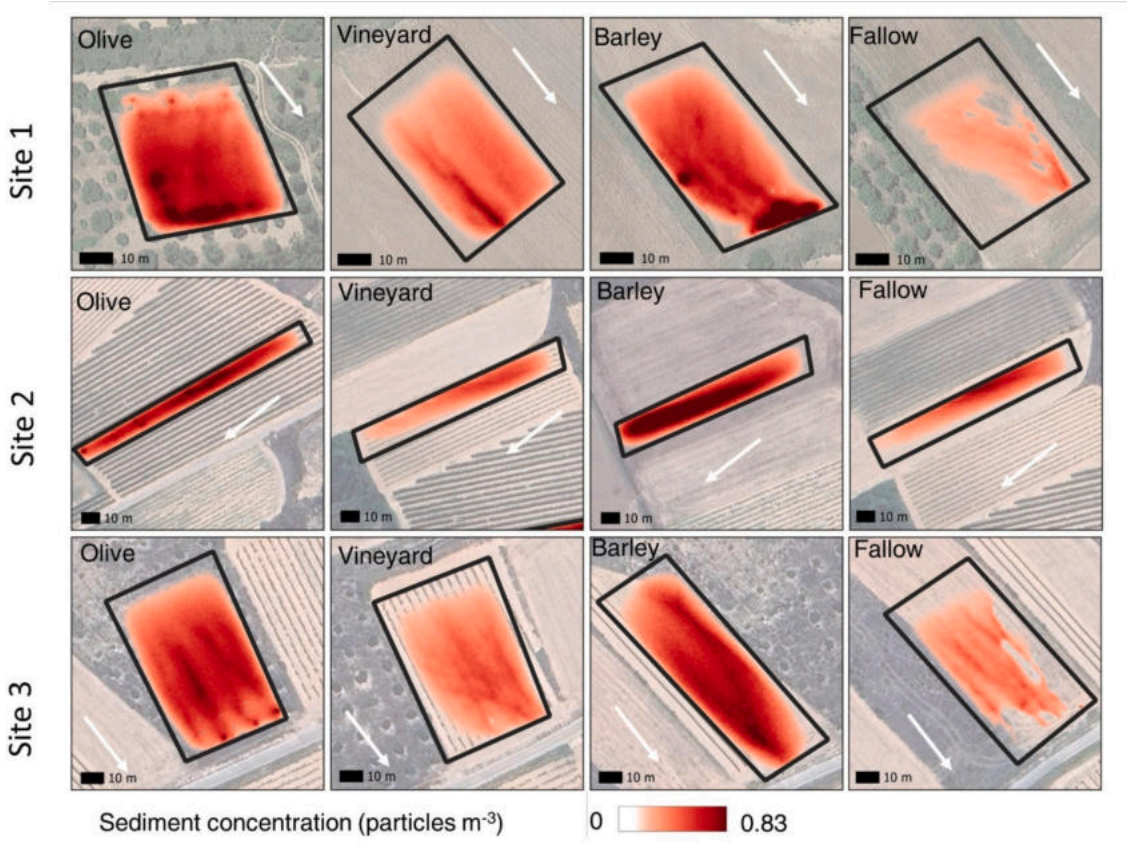

Fig. 5. Spatial distribution of sediment concentration for each land use and land cover in three experimental sites (the white arrow on each map indicates the direction of the slope).

Mediterranean landscape. Marzen et al. (2019) also found the highest rain erosion rates on crusted Mediterranean fallow land compared to other Mediterranean orchards, wheat fields, and vineyards through on-site water and wind erosion. These findings have also been reported by Zhang et al. (2015), who studied the impact of LULCs and slope steepness on soil erosion in a red soil hilly catchment in southern China, concluding that both crops and fallow land were the most important elements for contributing to soil erosion (Zhang et al., 2015). Nunes et al. (2011) present findings on the hydrological and erosional responses of soil to various LULCs in steep-slopes in Portugal. The study demonstrates that cropland and tree planting significantly accelerate overflow and soil erosion in these areas (Nunes et al., 2011). However, Maetens et al. (2012) analyzed the effects of various LULC types on water and soil loss in the Mediterranean region using the largest available database, comprising 1056 plots. Their results showed that vineyards and olive groves exhibited mean annual soil loss rates of 10–20 Mg ha^{-1} yr^{-1}, while cropland and fallow land accounted for only half (Maetens et al., 2012). For instance, some studies indicated that vineyards showed more higher erosion rate than the olive and spring crops (Cerdan et al., 2010), which is also inconsistent with our findings. One of the key factors contributing to the variation in results is the high spatio-temporal variability of runoff and soil loss processes and this instability complicates making an accurate assessment over an entire region or a longer period (Bagarello et al., 2011). In that sense, although LULCs involving crop cultivation (such as cropland, fallow, tree crops, and vineyards) generally exhibit higher mean soil loss rates compared to other LULCs under seminatural or natural vegetation (such as grassland, rangeland, shrubland and forest), high variability still exist within each LULC. These variations can only be partially explained by topographic factors, such as plot length and slope gradient. To improve the precision of such assessments, it is essential to isolate the effects of variables like vegetation cover and other variables such as slope gradient, slope length, and soil texture, and these should be strictly controlled. Numerous previous quantitative experimental studies have confirmed that plot-level studies conducted under natural rainfall conditions yield relatively more accurate results (Boix-Fayos et al., 2006; Cerdan et al., 2006; Maetens et al., 2012). However, modelling exercises enable the isolation of the effects of other variables, offering tools and results that can enhance land management scenarios.

4.2. *The role of fallow policy in water and soil conservation*

The Common Agricultural Policy (CAP) has impacted plant colonization and erosion rates over the past decades through its set-aside policy (van Leeuwen et al., 2019). This policy requires that farmers maintain their set-aside fields as either seeded fallow land with non-food crops or as unseeded fallow land through continuous ploughing to prevent plant colonization, to receive subsidies (García-Ruiz and Lana-Renault, 2011). Our results suggest that tilled, unseeded fallow lands introduced after the CAP policy result in a higher risk of severe soil erosion. Boellstorff and Benito (2005) also highlighted that although the unseeded fallow policy has contributed to water and soil conservation in some regions of Spain, it has increased the area that is at risk of severe erosion and has accelerated land degradation in the dryland of the country. Therefore, regional differences and environmental conditions should be considered in evaluating the role of fallow policy. Additionally, green fallow has been demonstrated to be beneficial for soil conservation and erosion mitigation, although it might not work well in dry areas (Rodriguez-Lloveras et al., 2016). Previous studies indicate that green fallow significantly enhances soil fertility, promotes carbon sequestration, and improves slope stability, making it a valuable strategy for sustainable land management (Cammeraat et al., 2005;

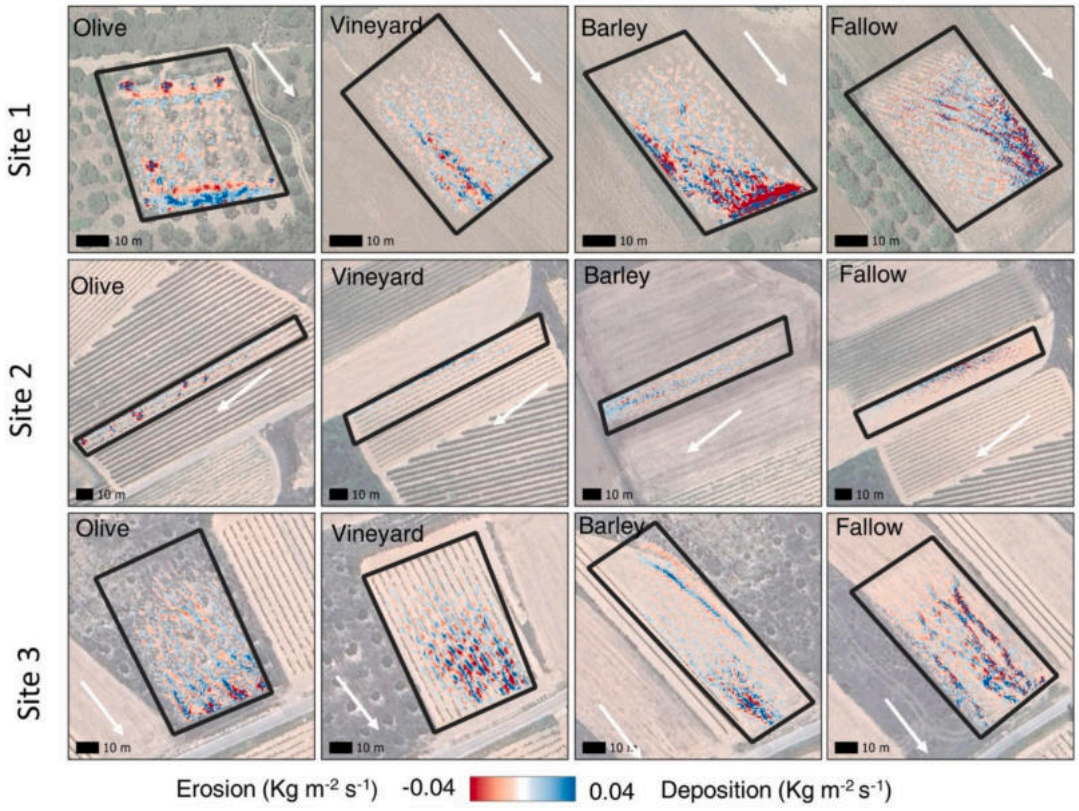

Fig. 6. Spatial distribution of erosion (values less than 0) and deposition (values greater than 0) for each of the land use and land cover classes of the 3 experimental sites (the white arrow on each map indicates the direction of the slope).

Żarczyński et al., 2023). An intriguing result from our study is that while fallow fields show the highest erosion rates and sediment fluxes, they also exhibit the lowest surface runoff and sediment concentrations. This phenomenon could be attributed to the high infiltration rate of fallow soils, which are more easily mobilized by subsurface water on slopes. Consequently, even with minimal surface runoff, significant sediment production can occur. Nielsen and Calderón (2011) state that the reason for fallowing is to store water in the soil profile to mitigate the effects of heavy rainfall. Such an objective has been confirmed by our study and by different studies, suggesting that fallow increases soil water storage, compared with crop systems. However, other studies suggested that fallow may not always increase infiltration in some specific precipitation events (Jones and Popham, 1997; Unger, 1992).

4.3. Effective LULC is critical in the sustainable development of steep-slope agriculture in facing climate change

Steep-slope agriculture is proven more fragile to climate change and is commonly distributed in mountain ridges and islands (Wang et al., 2022a). Even the impact of LULC change on the water and soil erosion process is more significant than the influence of climate change (Rodriguez-Lloveras et al., 2016). However, extreme rainstorm events can lead to soil losses in a short period that match the cumulative amount typically seen over several years (Meng et al., 2021; Valappil et al., 2024). In addition, Mediterranean mountains are identified as hotspots of climate warming in the coming decades, with projections indicating both an increase in temperature and extreme rainstorms (Wang et al., 2022b). In addition, regarding soil erosion processes, González-Hidalgo et al. (2007) found that, on average, the three largest daily events per year accounted for over 50 % of the total sediment carried out of the basin. Therefore, such events are significant under Mediterranean climate conditions, where intense rainstorms exceeding 200 mm in 24 h can trigger severe erosion processes, including the formation of gullies. Nadal-Romero et al. (2012) investigated the effect of large rainfall events on suspended sediment load under traditional and current LULC in Mediterranean mountains. The results confirm the importance of large rainfall events in explaining the geomorphological effects that occur and conclude that agricultural activities, especially in fallow land the more influenced LULC by the major impact of these events (Nadal-Romero et al., 2012). Given that steep-slope agricultural landscapes are particularly vulnerable to such climatic shifts, it is crucial to assess their resilience under extreme rainfall conditions. Thus, identifying effective LULC based on the response of water dynamics and soil erosion to extreme rainstorms is not only essential for developing effective soil and water conservation strategies and management practices but also crucial for enhancing resilience in steep-slope agriculture facing climate change. However, several studies indicate that extreme rainstorm events reduce the effectiveness of conservation measures and can result in short-term soil losses equal to the total losses over many years (García-Ruiz et al., 2013). In such cases, modelling exercises (despite their uncertainties and limitations) can be valuable tools for comparing and understanding the response to these events, offering recommendations for more sustainable agricultural practices. This study aims to apply a well-established physically-based modelling framework to diagnose and compare the hydro-sedimentary responses of different LULCs, focusing on addressing the research topic. Acknowledging that absolute erosion values might include model uncertainties, the comparative differences between LULC are robust because the same modeling assumptions and potential biases are systematically applied across all LULC without compromising the consistency or comparative validity of the findings to guide more sustainable agricultural practices related to public policies.

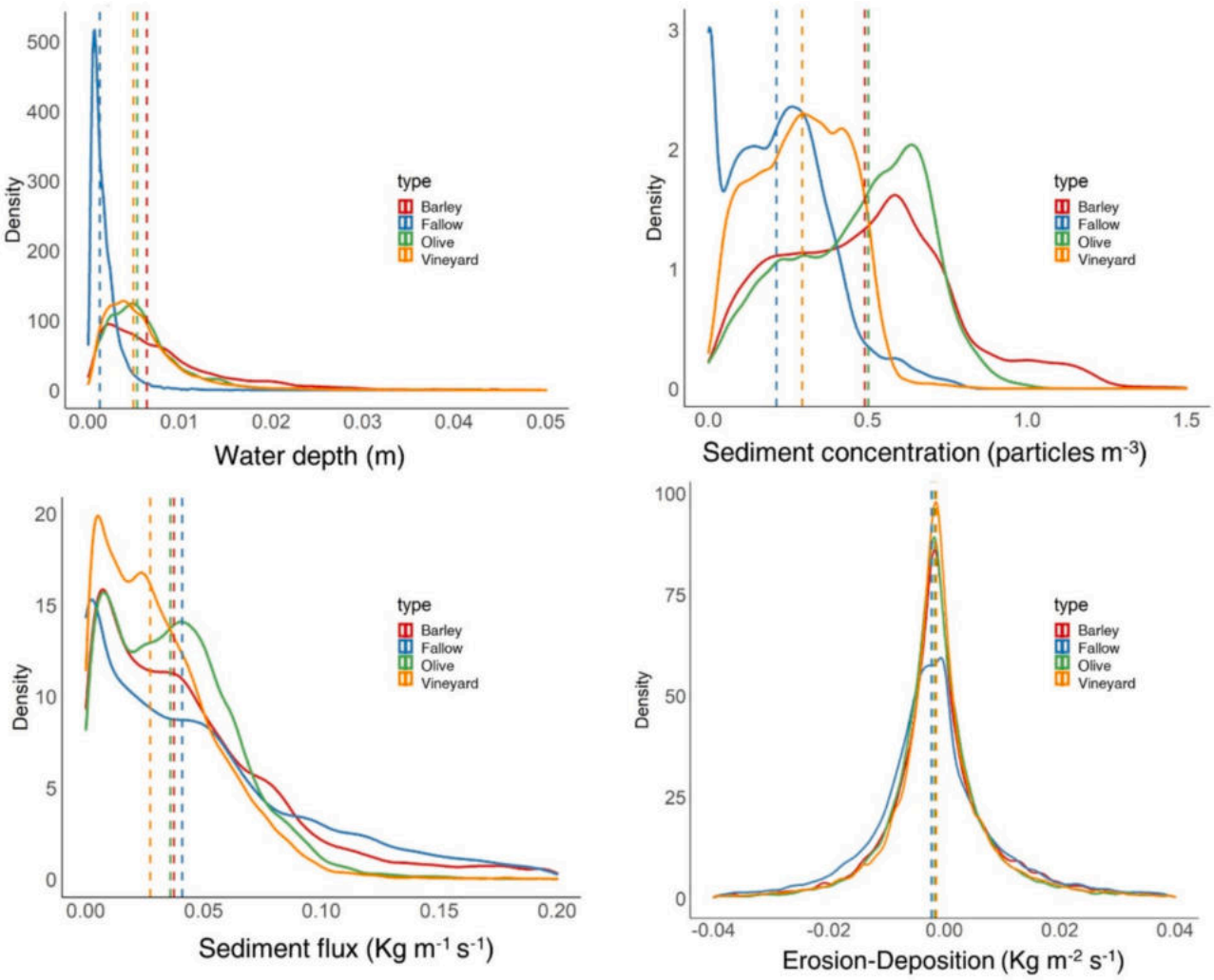

Fig. 7. The probability density functions illustrate the distribution of water depth, sediment flux, sediment concentration values, as well as erosion and deposition for different land use and land covers. The barley, fallow, olive, and vineyard are labelled as red, blue, green and yellow colour respectively. The median value for each crop type is represented by a dashed line. For example, barley is denoted by the red dashed line while fallow is depicted by the blue dashed line.

4.4. Limitations and future directions

Our study diagnostically compared the hydro-sedimentary responses of different land uses in steep-slope agriculture. A limitation lies in the lack of direct, field-based validation data to compare with our simulation results. However, we used a consolidated methodology, successfully tested in previous studies within similar agricultural settings, which confirmed the model's reliability through in-field observations (Pijl et al., 2022, 2020; Straffelini et al., 2022). For instance, Straffelini et al. (2022) conducted a two-year field study under comparable conditions, validating model outputs against measured runoff and sediment fluxes from single extreme rainfall events in vineyards with various grass cover treatments. Their findings confirmed that the model reliably captures the key dynamics of water and sediment movement following single extreme rainfall events, with acceptable and inevitable biases given its purpose for comparative analysis in complex agroecosystems and aligning with the scope of our work. Besides, the accuracy of the model highly sensitive to the precision of input parameters, and the real-world dynamics of water and soil movement on slopes are inherently complex and challenging to model. Future studies should focus on more on the model validation process to increase the accuracy and reliability of simulation results.

5. Conclusions

This study evaluated the effectiveness of water and soil conservation in four representative LULCs, including fallow, barley, vineyard, and olive in steep-slope agriculture in La Rioja (Spain). Our results demonstrate that sediment flux was significantly higher in unseeded fallow lands compared to the other uses, with barley, olive, and vineyard fields exhibiting progressively lower sediment fluxes. We surprisingly found the vineyard exhibited notably lower values for surface runoff, sediment concentration, and sediment flux compared to both olive and barley fields.

This finding provides new insight into local land management practices, suggesting that vineyards may be particularly effective in conserving water and soil compared to other LULCs in this region. However, a few aspects still need to be improved in this study. Future investigations should integrate multi-process assessments, combining different rainfall intensities, wind impacts, and solar radiation effects, to achieve a more comprehensive understanding of soil and water movement and the long-term effectiveness of conservation strategies under real-world conditions. In general, fallow lands indicated a higher risk of water and soil erosion, however, vineyard represents a promising cropland in terms of water and soil conservation on slopes in this region. This knowledge helps in mitigating soil erosion and implementing targeted interventions to prevent land degradation.

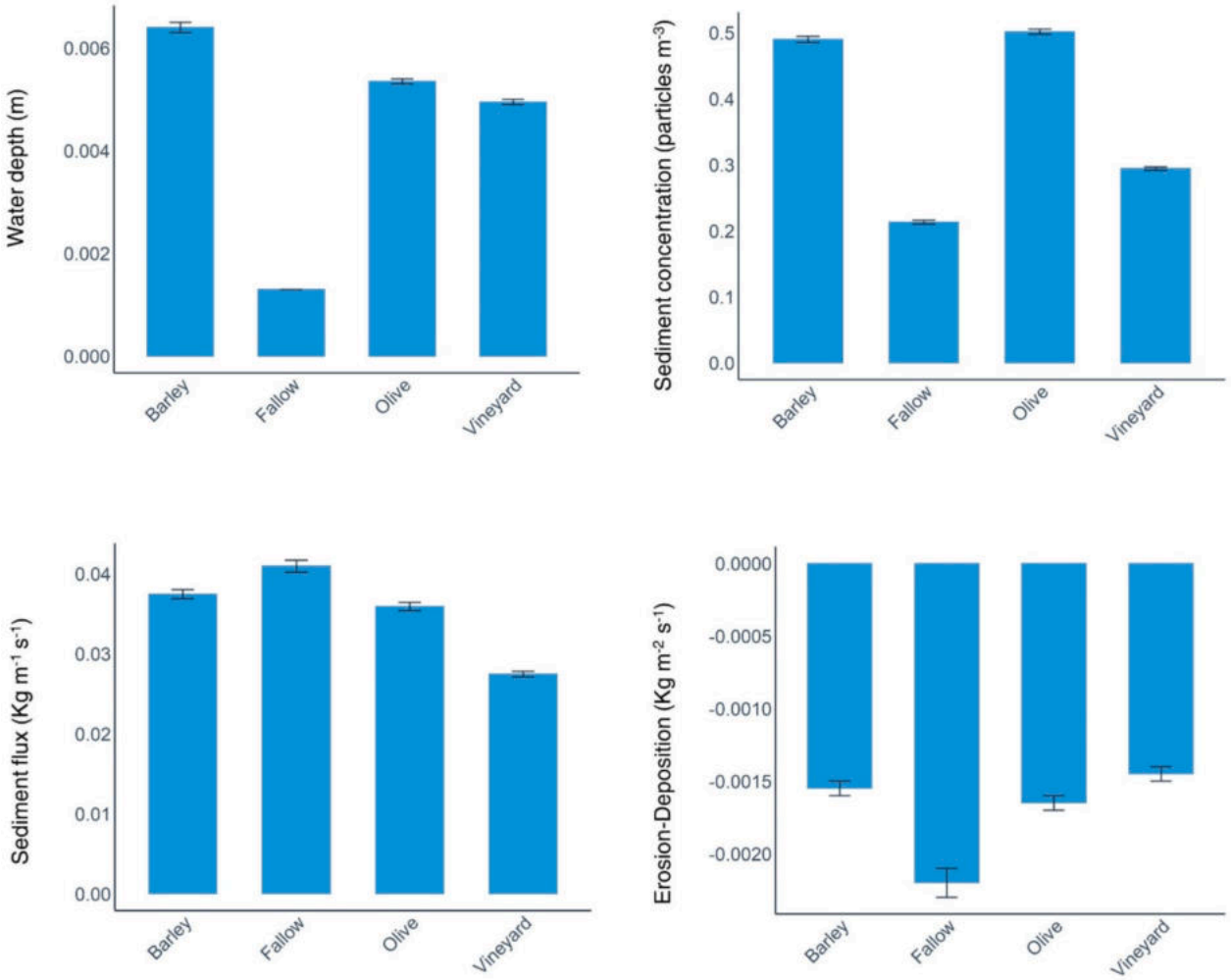

Fig. 8. Bootstrap confidence intervals for median value of water depth, sediment flux, sediment concentration values, as well as erosion and deposition for different land use and land covers.

CRediT authorship contribution statement

Wendi Wang: Writing – original draft, Methodology, Investigation, Conceptualization. **Manel Llena:** Writing – review & editing, Supervision, Methodology. **Estela Nadal-Romero:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Teodoro Lasanta:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Paolo Tarolli:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

wendiwang-data/CATENA (Original data) (GitHub)

References

Arnaez, J., Lasanta, T., Errea, M.P., Ortigosa, L., 2011. Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: the case of Camero Viejo L. Degrad. Dev. 22, 537–550. https://doi.org/10.1002/ldr.1032.

Bagarello, V., Di Stefano, C., Ferro, V., Pampalone, V., 2011. Using plot soil loss distribution for soil conservation design. Catena 86, 172–177. https://doi.org/10.1016/j.catena.2011.03.009.

Boellstorff, D., Benito, G., 2005. Impacts of set-aside policy on the risk of soil erosion in central Spain. Agric. Ecosyst. Environ. 107, 231–243. https://doi.org/10.1016/j.agee.2004.11.002.

Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalén, E., Calvo-Cases, A., Castillo, V., Albaladejo, J., 2006. Measuring soil erosion by field plots: understanding the sources of variation. Earth-Sci. Rev. 78, 267–285. https://doi.org/10.1016/j.earscirev.2006.05.005.

Cammeraat, E., van Beek, R., Kooijman, A., 2005. Vegetation succession and its consequences for slope stability in SE Spain. Plant and Soil 278, 135–147. https://doi.org/10.1007/s11104-005-5893-1.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122, 167–177.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., 2006. Sheet and rill erosion. In: Soil Erosion in Europe. https://doi.org/10.1002/0470859202.ch38.

Durán Zuazo, V.H., Francia Martínez, J.R., Rodríguez Pleguezuelo, C.R., Martínez Raya, A., Cárceles Rodríguez, B., 2006. Soil-erosion and runoff prevention by plant covers in a mountainous area (SE Spain): Implications for sustainable agriculture. Environmentalist 26, 309–319. https://doi.org/10.1007/s10669-006-0160-4E.

Feldmann, D., Laux, P., Heckl, A., Schindler, M., Kunstmann, H., 2023. Near surface roughness estimation: a parameterization derived from artificial rainfall experiments and two-dimensional hydrodynamic modelling for multiple vegetation coverages. J. Hydrol. 617, 128786. https://doi.org/10.1016/j.jhydrol.2022.128786.

Fernandes, J., Bateira, C., Soares, L., Faria, A., Oliveira, A., Hermenegildo, C., Moura, R., Gonçalves, J., 2017. SIMWE model application on susceptibility analysis to bank gully erosion in Alto Douro Wine Region agricultural terraces. Catena 153, 39–49. https://doi.org/10.1016/j.catena.2017.01.034.

García-Orenes, F., Cerdà, A., Mataix-Solera, J., Guerrero, C., Bodí, M.B., Arcenegui, V., Zornoza, R., Sempere, J.G., 2009. Effects of agricultural management on surface soil properties and soil-water losses in eastern Spain. Soil Till. Res. 106 (1), 117–123. https://doi.org/10.1016/j.still.2009.06.002.

García-Ruiz, J.M., 2010. The effects of land uses on soil erosion in Spain: a review. Catena 81, 1–11. https://doi.org/10.1016/j.catena.2010.01.001.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region – a review. Agric. Ecosyst. Environ. 140, 317–338. https://doi.org/10.1016/j.agee.2011.01.003.

García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N., Beguería, S., 2013. Erosion in Mediterranean landscapes: changes and future challenges. Geomorphology 198, 20–36. https://doi.org/10.1016/j.geomorph.2013.05.023.

García-Ruiz, J.M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J.C., Lana-Renault, N., Sanjuán, Y., 2015. A meta-analysis of soil erosion rates across the world. Geomorphology 239, 160–173. https://doi.org/10.1016/j.geomorph.2015.03.008.

Gómez, J.A., Infante-Amate, J., González de Molina, M., Vanwalleghem, T., Taguas, E.V., Lorite, I., 2014. Olive cultivation, its impact on soil erosion and its progression into yield impacts in Southern Spain in the past as a key to a future of increasing climate uncertainty. Agriculture 4, 170–198. https://doi.org/10.3390/agriculture4020170.

González-Hidalgo, J.C., Peña-Monné, J.L., de Luis, M., 2007. A review of daily soil erosion in Western Mediterranean areas. Catena 71, 193–199. https://doi.org/10.1016/j.catena.2007.03.005.

Gonzalo Moreno, A.N., 1981. El relieve de La Rioja. Análisis de geomorfología estructural. Bibl. Temas Riojanos, Inst. Estud. Riojanos 1–508.

Jones, O.R., Popham, T.W., 1997. Cropping and tillage systems for dryland grain production in the Southern High Plains. Agron. J. 89, 222–232. https://doi.org/10.2134/agronj1997.00021962008900020012x.

Khorchani, M., Nadal-Romero, E., Tague, C., Lasanta, T., Zabalza, J., Lana-Renault, N., Domínguez-Castro, F., Choate, J., 2020. Effects of active and passive land use management after cropland abandonment on water and vegetation dynamics in the Central Spanish Pyrenees. Sci. Total Environ. 717, 137160. https://doi.org/10.1016/j.scitotenv.2020.137160.

Koco, Š., 2011. Simulation of gully erosion using the SIMWE model and GIS. Landf. Anal. 17, 81–86.

Larson, W.E., Pierce, F.J., Dowdy, R.H., 1983. The threat of soil erosion to long-term crop production. Science (80-.). 219, 458–465. https://doi.org/10.1126/science.219.4584.458.

Lasanta, T., Arnaez, J., Oserín, M., Ortigosa, L.M., 2001. Marginal lands and erosion in terraced fields in the Mediterranean mountains: a case study in the Camero Viejo (Northwestern Iberian System, Spain). Mt. Res. Dev. 21 (1), 69–76. https://doi.org/10.1659/0276-4741(2001)021[0069:MLAEIT]2.0.CO;2.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M.P., Lana-Renault, N., 2017. Space–time process and drivers of land abandonment in Europe. Catena 149, 810–823. https://doi.org/10.1016/j.catena.2016.02.024.

Llena, M., Nadal-Romero, E., Zabalza-Martínez, J., Cortijos-López, M., Lasanta, T., 2024. Effects of post-abandonment management on surface runoff in a Mediterranean mid-mountain basin. Catena 237, 107775. https://doi.org/10.1016/j.catena.2023.107775.

Maetens, W., Vanmaercke, M., Poesen, J., Jankauskas, B., Jankauskiene, G., Ionita, I., 2012. Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: a meta-analysis of plot data. Prog. Phys. Geogr.: Earth Environ. 36, 599–653. https://doi.org/10.1177/0309133312451303.

Meng, X., Zhu, Y., Yin, M., Liu, D., 2021. The impact of land use and rainfall patterns on the soil loss of the hillslope. Sci. Rep. 11, 16341. https://doi.org/10.1038/s41598-021-95819-5.

Miró, J.J., Lemus-Canovas, M., Serrano-Notivoli, R., Olcina Cantos, J., Estrela, M.J., Martin-Vide, J., Sarricolea, P., Meseguer-Ruiz, O., 2022. A component-based approximation for trend detection of intense rainfall in the Spanish Mediterranean coast. Weather Clim. Extrem. 38, 100513. https://doi.org/10.1016/j.wace.2022.100513.

Mitas, L., Mitasova, H., 1998. Distributed soil erosion simulation for effective erosion prevention. Water Resour. Res. 34, 505–516. https://doi.org/10.1029/97WR03347.

Moret, D., Arrúe, J.L., López, M.V., Gracia, R., 2006. Influence of fallowing practices on soil water and precipitation storage efficiency in semiarid Aragon (NE Spain). Agric Water Manag 82, 161–176. https://doi.org/10.1016/j.agwat.2005.07.019.

Myhre, G., Alterskjær, K., Stjern, C.W., Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Sci. Rep. 9, 16063. https://doi.org/10.1038/s41598-019-52277-4.

Nadal-Romero, E., García-Ruiz, J.M., 2025. Market as a factor in soil erosion: the expansion of new and old crops into marginal Mediterranean lands. Reg. Environ. Chang. 25, 16. https://doi.org/10.1007/s10113-024-02355-9.

Nadal-Romero, E., Lasanta Martínez, T., González-Hidalgo, J.C., de Luis Arrillaga, M., García-Ruiz, J.M., 2012. The effect of intense rainstorm events on the suspended sediment response under various land uses: the Aísa Valley Experimental Station. Cuadernos De Investigación Geográfica 38 (1), 27–47. https://doi.org/10.18172/cig.1274.

Nadal-Romero, E., Lasanta, T., García-Ruiz, J.M., 2013. Runoff and sediment yield from land under various uses in a Mediterranean mountain area: long-term results from an experimental station. Earth Surf. Process. Landforms 38, 346–355. https://doi.org/10.1002/esp.3281.

Neteler, M., Mitasova, H., 2002. Open Source GIS: A GRASS GIS approach. Springer Science & Business Media.

Nielsen, D.C., Calderón, F.J., 2011. Fallow effects on soil. Soil Manag. Build. a stable base Agric., 287–300.

Nunes, A.N., de Almeida, A.C., Coelho, C.O.A., 2011. Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. Appl. Geogr. 31, 687–699. https://doi.org/10.1016/j.apgeog.2010.12.006.

Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M., Poesen, J., Borrelli, P., 2021. Projections of soil loss by water erosion in Europe by 2050. Environ. Sci. Policy 124, 380–392. https://doi.org/10.1016/j.envsci.2021.07.012.

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., Montanarella, L., 2015a. Estimating the soil erosion cover-management factor at the European scale. Land Use Policy 48, 38–50. https://doi.org/10.1016/j.landusepol.2015.05.021.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015b. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012.

Pijl, A., Reuter, L.E.H., Quarella, E., Vogel, T.A., Tarolli, P., 2020. GIS-based soil erosion modelling under various steep-slope vineyard practices. Catena 193, 104604. https://doi.org/10.1016/j.catena.2020.104604.

Pijl, A., Wang, W., Straffelini, E., Tarolli, P., 2022. Soil and water conservation in terraced and non-terraced cultivations: an extensive comparison of 50 vineyards. L. Degrad. Dev. 33, 596–610. https://doi.org/10.1002/ldr.4170.

Recuero, L., Wiese, K., Huesca, M., Cicuéndez, V., Litago, J., Tarquis, A.M., Palacios-Orueta, A., 2019. Fallowing temporal patterns assessment in rainfed agricultural areas based on NDVI time series autocorrelation values. Int. J. Appl. Earth Obs. Geoinf. 82, 101890. https://doi.org/10.1016/j.jag.2019.05.023.

Renard, K.G., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture, Agricultural Research Service.

Ribes, A., Thao, S., Vautard, R., Dubuisson, B., Somot, S., Colin, J., Planton, S., Soubeyroux, J.-M., 2019. Observed increase in extreme daily rainfall in the French Mediterranean. Clim. Dyn. 52, 1095–1114. https://doi.org/10.1007/s00382-018-4179-2.

Rodriguez-Lloveras, X., Buytaert, W., Benito, G., 2016. Land use can offset climate change induced increases in erosion in Mediterranean watersheds. Catena 143, 244–255. https://doi.org/10.1016/j.catena.2016.04.012.

Romero, P., Castro, G., Gómez, J.A., Fereres, E., 2007. Curve NUMBER values for olive orchards under different soil management. Soil Sci. Soc. Am. J. 71, 1758–1769. https://doi.org/10.2136/sssaj2007.0034.

Straffelini, E., Pijl, A., Otto, S., Marchesini, E., Pitacco, A., Tarolli, P., 2022. A high-resolution physical modelling approach to assess runoff and soil erosion in vineyards under different soil managements. Soil Tillage Res. 222, 105418. https://doi.org/10.1016/j.still.2022.105418.

Tarolli, P., Straffelini, E., Pijl, A., Otto, S., Marchesini, E., Pitacco, A., Tarolli, P., 2022. A high-resolution physical modelling approach to assess runoff and soil erosion in vineyards under different soil managements. Soil Tillage Res. 222, 105418. https://doi.org/10.1016/j.still.2022.105418.

Ullrich, A., Volk, M., 2009. Application of the Soil and Water Assessment Tool (SWAT) to predict the impact of alternative management practices on water quality and quantity. Agric Water Manag 96, 1207–1217. https://doi.org/10.1016/j.agwat.2009.03.010.

Unger, P.W., 1992. Infiltration of simulated rainfall: tillage system and crop residue effects. Soil Sci. Soc. Am. J. 56, 283–289. https://doi.org/10.2136/sssaj1992.03615995005600010045x.

Valappil, N.K.M., Ahmad, F.S., Mammen, P.C., Shobhana, P.G.N., Hamza, V., 2024. Temporal soil loss scenarios and erosional dynamics of a slopping landmass in the southwestern India before and after the 2018 severe rainfall and mega flood events. Nat. Hazards 1–28. https://doi.org/10.1007/s11069-024-06790-z.

van Leeuwen, C.C.E., Cammeraat, E.L.H., de Vente, J., Boix-Fayos, C., 2019. The evolution of soil conservation policies targeting land abandonment and soil erosion in Spain: a review. Land Use Pol. 83, 174–186. https://doi.org/10.1016/j.landusepol.2019.01.018.

Wang, W., Pijl, A., Tarolli, P., 2022a. Future climate-zone shifts are threatening steep-slope agriculture. Nat. Food 3, 193–196. https://doi.org/10.1038/s43016-021-00454-y.
Wang, W., Straffelini, E., Pijl, A., Tarolli, P., 2022b. Sustainable water resource management in steep-slope agriculture. Geogr. Sustain. 3 (3), 214–219. https://doi.org/10.1016/j.geosus.2022.07.001.
Żarczyński, P.J., Krzebietke, S.J., Sienkiewicz, S., Wierzbowska, J., 2023. The role of fallows in sustainable development. Agriculture 13, 2174. https://doi.org/10.3390/agriculture13122174.
Zhang, Z., Sheng, L., Yang, J., Chen, X.-A., Kong, L., Wagan, B., 2015. Effects of land use and slope gradient on soil erosion in a red soil hilly watershed of southern China. Sustainability 7, 14309–14325. https://doi.org/10.3390/su71014309.
Zittis, G., Bruggeman, A., Lelieveld, J., 2021. Revisiting future extreme precipitation trends in the Mediterranean. Weather Clim. Extrem. 34, 100380. https://doi.org/10.1016/j.wace.2021.100380.

Further reading

Lampurlanés, J., Angás, P., Cantero-Martínez, C., 2002. Tillage effects on water storage during fallow, and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. Soil Tillage Res. 65, 207–220. https://doi.org/10.1016/S0167-1987(01)00285-9.
Wang, W., Straffelini, E., Tarolli, P., 2021. Soil and water conservation in terraced and non-terraced cultivations - a massive comparison of 50 vineyards 1–5.
Pijl, A., Cucchiaro, S., Wei, W., 2021. Slope instabilities in steep cultivation systems: Process classification and opportunities from remote sensing. L. Degrad. Dev. 32 (2), 1368–1388. https://doi.org/10.1002/ldr.3798.