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Soil erosion control in a pasture-dominated Mediterranean mountain environment under global change

Laurène Marien[1,2] | Rossano Ciampalini[1,3] | Feliciana Licciardello[4] | Emanuela Rita Giuffrida[4] | Amandine Valérie Pastor[1,5,6] | Frederic Huard[7] | Damien Raclot[1]

[1]LISAH, INRAE, IRD, Institut Agro, University of Montpellier, Montpellier, France
[2]G-EAU, CIRAD, INRAE, Institut Agro, IRD, University of Montpellier, Montpellier, France
[3]DST, University of Florence, Firenze, Italy
[4]Di3A, University of Catania, Santa Sofia, Catania, Italy
[5]cE3c, Universidade de Lisboa, Lisbon, Portugal
[6]ITAP-Elsa, Univ Montpellier, INRAE, Institut Agro, Montpellier, France
[7]US 1116 AgroClim, INRA, Avignon, France

Correspondence
Laurène Marien, G-EAU, CIRAD, INRAE, Institut Agro, IRD, University of Montpellier, 2 place Pierre Viala, 34070 Montpellier, France.
Email: laurene.marien@supagro.fr

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Abstract

Soil erosion control is critical to global food production and ecosystem health worldwide, and particularly in the Mediterranean region, which is prone to erosion and is expected to be strongly affected by climatic and anthropogenic changes. In this paper, we explore how land use and management (LUM) can mitigate climate change impacts and increase agricultural attractiveness in pasture-dominated Mediterranean mountain environments. One originality of the proposed research is to combine LUM scenarios incorporating environmental and socio-economic behaviour with distributed process-based modelling to simulate the impacts of global change. Specifically, soil erosion for different combinations of current and plausible future climate and LUM conditions were simulated on a small watershed located in eastern Sicily (Italy) using the LandSoil model. LUM scenarios were established as a modulation of environmental protection and agricultural production/diversification. The main management distinctions tested in this paper included intensive versus extensive practices for pasture, and conventional versus conservative practices for cereals and orchards. Simulations showed that the impact of climate change was very low and not significant in the studied watershed (i.e., −1.78% of erosion on average). Under current climate and compared to the baseline, LUM scenarios reported an increase in erosion for the business-as-usual (S1, +6.0%), market-oriented (S2, +57.2%) and sustainability-oriented (S4, +0.9) scenarios, respectively, whereas the nature-oriented scenario led to a slight reduction in erosion (S3, −11.3%). Our results also emphasised that agricultural diversification coupled with adaptations in practices and management can improve the attractiveness of agriculture in pasture-dominated environments while maintaining soil protection at an acceptable level.

KEYWORDS
agriculture diversification, global change, Mediterranean pasture lands, mitigation measures, soil erosion modelling, soil protection

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1 | INTRODUCTION

Soil is a natural resource essential for many ecosystem functions such as supplying nutrients, water or energy and regulating climate, flooding, erosion, and so forth (Baer & Birgé, 2018; Schwilch et al., 2015; Tibi & Therond, 2018). Soil is also a very fragile system, and its degradation can be very rapid when unfavourable physical, topographic, climatic or anthropogenic conditions are reached (Amundson et al., 2015; Poesen, 2018). The Mediterranean area exhibits high levels of soil erosion (Cerdan et al., 2010; Vanmaercke et al., 2011; Woodward, 1995), which is one of the primary causes of land degradation and is responsible for many environmental issues (ITPS, 2015; Le Bissonnais et al., 1998). The principal factors respond to climatic behaviours such as frequent and heavy rainfall events (Li & Fang, 2016), continuous cropping over areas with shallow soil thickness (Fu et al., 2011), induced loss of soil organic matter (EIP-AGRI Focus Group, 2016), lack of management practices for conservation (Panagos et al., 2015) and long-term human occupation with intensive cultivations (Butzer, 2005; de Franchis & Ibanez, 2003; Kosmas et al., 2002; Raclot et al., 2017; Zdruli, 2014). In the context of global change, it seems important to define sustainable management strategies to ensure soil resource conservation (Lagacherie et al., 2017) as well as to identify efficient and attractive options among the possible trajectories. Once the nature and the intensity of soil erosion processes are as diverse as the mosaic of the Mediterranean landscape, tailor-made site strategies must be defined for each agro-ecosystem (Raclot et al., 2017).

In this paper, we focus on a Mediterranean agro-ecosystem dominated by pasture. This kind of environment occupies a large part of the Mediterranean area as grasslands and shrublands cover, respectively, 21.3% and 24.0% of the surface, most of which are used for permanent pasture (Guarino et al., 2020). Moreover, pastureland is expected to increasingly replace cultivated land in Europe (Panagos et al., 2021). As for other Mediterranean agro-ecosystems, climate change represents a major threat because more intense and frequent periods of drought and extreme rainfall are expected to occur (IPCC, 2023; Tramblay & Somot, 2018). As a result of these extremes, soil degradation due to water erosion is expected to increase (Gonzales-Hidalgo et al., 2007), necessitating land-use and management mitigation measures. Aguilera et al. (2020) studying the adaptation to climate change and resource depletion through agro-ecological strategies noted that pasture management can be crucial in mitigating the negative effects of climate change on soil properties and livestock. In recent decades, Mediterranean regions have undergone consistent changes in land use and management (LUM) interventions in response to demography and agricultural economy, leading to elaborate patterns in which intensive and extensive practices and land abandonment coexist (García-Ruiz et al., 2013, 2020; García-Ruiz & Lana-Renault, 2011). According to the authors, these changes have a major impact on soil erosion and land degradation. In Italy, such changes resulted in a generalised land abandonment, occasionally associated with the expansion of intensive practices, including overgrazing (see Supporting Information Appendix A for a short retrospective of land use dynamics in Sicily from the XIX century).

In the literature, various studies have addressed the question of which land management strategies could be adopted in a sound and cost-effective manner, what the role of extensive versus intensive practices should be in soil protection and which land use policies should be preferable in landscapes dominated by grazing. For example, Peco et al. (2017), testing the extensive grazing impact on soil functions and quality, report that abandonment can generally lead to a decline in soil quality such as nutrients availability, aggregate stability, organic matter content as well as water retention capability with an increase in soil loss. As a consequence, they noted that 'agri-environmental policies should be aware of the risk of widespread grazing abandonment and take advantage of the benefits of low-intensity grazing regimes for ecosystem services such as soil fertility and stability, and soil carbon storage'. As noticed by Yirdaw et al. (2017) in a review of the state-of-knowledge about the rehabilitation of degraded drylands, the impact of livestock grazing is ambivalent as it is sometimes seen as a cause of rangeland degradation (Müller et al., 2007) and soil erosion (Mekuria & Aynekulu, 2011), whereas other studies mentioned its long-term positive effect on pasture vegetation productivity (Cheng et al., 2009; Kgosikoma et al., 2015; Perevolotsky & Seligman, 1998; Yayneshet & Treydte, 2015). They also indicated that the choice of grazing system management can be the dominant driver in rangeland degradation (Gulelat, 2002; Savadogo et al., 2008) and that the risk of rangeland degradation can therefore be minimised by using grazing management systems based on better regulation of livestock density and grazing frequency (Jouven et al., 2010; Lindeque, 2011; van Oudenhoven et al., 2015). Given the uncertainties surrounding future projections, particularly climatic, Centeri (2022) suggested that the solution for the future must also include diversification of land use.

Modelling approaches provide a useful tool for anticipating the impact of global change on soil resources, identifying sustainable adaptation or mitigation strategies, and understanding the multiple dynamics that converge on rangelands (Martínez-Valderrama & Ibáñez Puerta, 2023). Numerous recent studies based on distributed physical process-based modelling approaches (e.g., Bussi et al., 2014; Nunes et al., 2017; Nunes & Nearing, 2010; Serpa et al., 2015; Simonneaux et al., 2015) have shown that the intensity of impacts and the nature of solutions are highly dependent on biophysical and anthropic local factors. Yet, very few studies have used a modelling approach for upland Mediterranean grazing agroecosystems. Among them, Martínez-Valderrama and Ibáñez Puerta (2023) have developed and applied a holistic approach based on system dynamics that, in particular, allows components of socio-economic behaviour to be integrated into simulations. However, the empirical nature of the (biophysical) process descriptions in such models may hamper their predictive capability, especially when focusing on small-scale applications in a context of global change (see Guo et al., 2019 for an extensive discussion on the limitations and future challenges of soil and water erosion models in a context of global change). To our knowledge, the other studies have focused on the relationships between environmental conditions and animal stocks without explicitly considering socio-economics factors. This study aims to continue these modelling efforts by seeking a compromise that improves the attractiveness and resilience of mountain grazing agroecosystems while providing a good level of soil protection. Its main originality is to consider socio-economic behaviour and agriculture diversification into scenarios, which are then simulated through distributed physical process-based modelling that are necessary for predicting the impacts of global change. Indeed, some compromises are needed to meet the challenge of reconciling agricultural production, environmental protection and the effects of climate change. This subject is still the focus of much research and in this paper, we assessed the impact of global change scenarios on soil loss in a pasture-dominated watershed on the slopes of Mount Etna (Cannata, Italy) by 2050 testing strategies to maintain and diversify agricultural production while protecting soil resources. With this purpose, we modelled soil erosion with the distributed and process-based LandSoil model (Ciampalini et al., 2012, 2017) over two 20-year periods, past and future periods, under RCP4.5 scenario emission. We quantified the impact of LUM on runoff and erosion using four scenarios derived from the combination of plausible socio-economic conditions and organised into two main axes: productivity (i.e., agricultural production) and protection (i.e., soil conservation) (Pastor et al., 2022). The principal management distinctions included intensive versus extensive practices for pasture, and conventional versus conservative practices for cereals and orchards.

2 | MATERIALS AND METHODS

2.1 | Study area

This research was conducted in the Cannata catchment (Figure 1), a small watershed of 130 ha in Eastern Sicily (37° 53′ 5" N, 14° 52′ 48″ E) on the nearby slopes of the Etna volcano. Crossed by the river Flascio, it has an elevation ranging from 903 and 1270 m a.s.l. and an average slope of 21%.

The catchment has a sub-humid Mediterranean climate with average annual rainfall (years 1996–2005) of 715 ± 163 mm and mean monthly temperature of 6°C in January and 24°C in August. The Cannata basin belongs to the Monte Soro Flysch unit (Lower Cretaceous), locally as a part of a thrust system involving the Numidian Flysch and the Upper Argille Scagliose unit (Coccioni & Monechi, 1994; ISPRA AMBIENTE, 2018). The lithology of the catchment is mostly clayey-

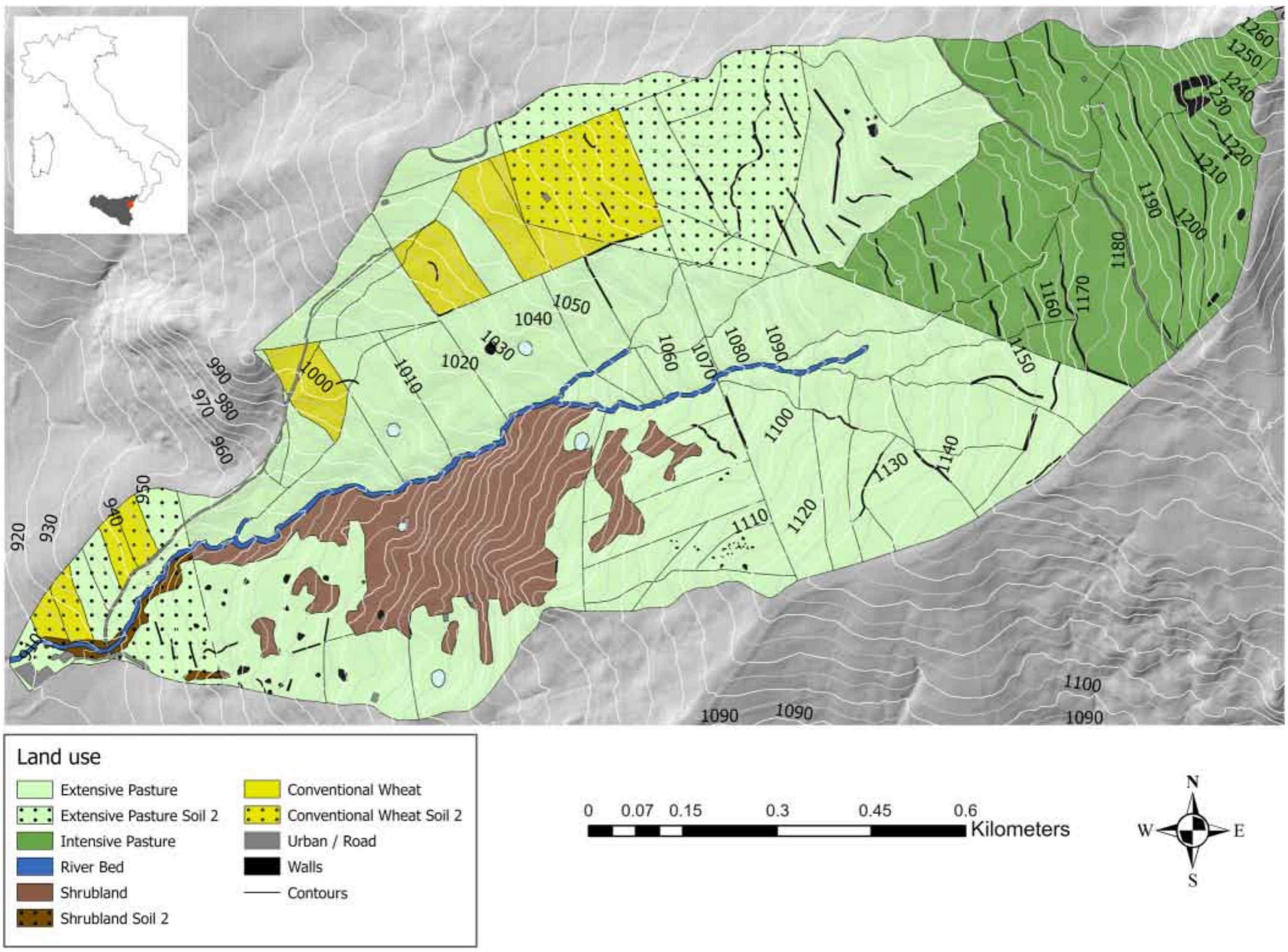

FIGURE 1 Land use, soil types and relief (contour lines and shaded view) of Cannata catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 The tested combination of LUM and climate and LUM scenarios.

	Combination name	LUM scenario	Climate time series
Baseline	S0-H	S0	1985–2004
Climate change only	S0-F	S0	2040–2059
LUM change only	S1-H	S1	1985–2004
	S2-H	S2	1985–2004
	S3-H	S3	1985–2004
	S4-H	S4	1985–2004
Combined change in climate and LUM	S1-F	S1	2040–2059
	S2-F	S2	2040–2059
	S3-F	S3	2040–2059
	S4-F	S4	2040–2059

Abbreviation: LUM, land use and management.

calcareous in the lower part, clay/clayey-arenaceous in the medium-high and more arenaceous in the higher part. The soils of the area (Ballatore & Fierotti, 1967) consist of shallow, clayey, few developed soils (Leptosols; IUSS Working Group WRB, 2022). A survey of the area (Licciardello, Barbagallo, & Gallart, 2019) indicates soil generally spreading up to 0.7 m, with depths up to 30 cm mainly located in the upper part of the catchment and representing about 30%; in 5% of the area, the soil attains a depth of 1 m. Soil texture (Soil Survey Staff, 2014) is mainly clay-loam (63%), secondarily loam (21%), loam-sand (10.5%), clay (3.5%) and loam-sand-clay (2.0%); the skeleton has values ranging from 2.3% and 36.8%. The saturated hydraulic conductivity, referred to a depth of 10–15 cm, ranges from 0.2 to 17.6 mm.h^{-1}. The catchment is hydrologically classified as intermittent-flow type (Gallart et al., 2002; Licciardello et al., 2009). Diffuse erosion is the most commonly observed process, while linear erosion is rarely found. Runoff can concentrate in mid-low parts of the basin as shown by the presence of few sparse shallow gullies. When it occurs, the discontinuous ephemeral gullies do not exceed 0.4 m in depth and 5 m in length. Few shallow mass movements can also be observed in the basin, especially at the margins of stream channels (Licciardello, Barbagallo, & Gallart, 2019). The current LUM (Table 1) includes extensive pasture (61.62%), intensively managed pasture (19.42%), conventionally managed wheat (7.03%) and shrubland (9.36%). The livestock grazing in the study area is mainly a mixture of sheep and goats, that is small ruminants, although a few cows may occasionally be present. Additional catchment characteristics, vegetation description and sampling information are reported by Licciardello and Zimbone (2002).

2.2 | The LandSoil model

We simulated soil erosion with LandSoil model (Ciampalini et al., 2012, 2017) for water and tillage erosion processes, which is event-based (i.e., rainfall and tillage) and considers landscape topography evolution according to the soil redistribution processes over medium-long terms. The model uses decision rules built on a large database of observed data (Cerdan et al., 2002; Le Bissonnais et al., 1998), which defines the parameters for the tendency of runoff, sediment concentration and producing concentrated erosion on the basis of soil surface conditions and rainfall characteristics. Runoff is routed through the catchment according to a D8 directional topographic flow redistribution model (Jenson & Domingue, 1988) modified to include tillage and the main linear features driving flows inside the catchment (Souchère et al., 1998).

Water erosion, including linear and diffuse erosion, is calculated by associating water and sediment production functions with transfer functions governed by topographic laws and connectivity between cells. Linear erosion component responds to a classical formulation (Kirkby et al., 2008) integrating soil erodibility, runoff volume and slope parameters according to rules following the physical properties of the soil (i.e., friction and cohesion) at the surface (Cerdan et al., 2002; Souchère et al., 2003). Diffuse erosion (i.e., referred to the soil particles detached by splash erosion and remobilised by runoff) is controlled by the combination of the soil surface properties and rainfall characteristics based on rainfall and field runoff observations (Cerdan et al., 2002). The corresponding soil properties interacting with the runoff erosive processes are defined by Le Bissonnais et al. (1998, 2005) according to vegetation cover, soil roughness and soil crusting combination. Tillage erosion responds to diffusion rules as experienced by Govers et al. (1994) following a monthly tillage schedule for each plot, based on land use and cropping pattern, and specific tillage redistribution constants for each practice and tool.

A rainfall time series is provided to the model in the form of a succession of rain events including effective precipitation (mm), rainfall duration (h), precipitation over the 48 hours preceding the event (mm) and maximum intensity over 5 min (mm h^{-1}).

The model is sediment-concentration limited, with restrictions determined by a combination of soil and topographic conditions. This corresponds to a maximum allowable sediment concentration between 2.5 and 10 g l^{-1} for specific values of topography (i.e., concavity >0.055 m^{-1} and slope gradient <0.02 mm^{-1}), land cover (>60%) and land uses with high vegetation cover. The LandSoil model iteratively provides maps for the spatial distribution of the variables used, runoff, diffuse, linear and tillage erosion, and a resulting topographic surface after each rainfall and tillage event. The net soil erosion (mm year^{-1} or t ha^{-1} year^{-1}), referring to the combined on-site impacts of soil ablation or deposition, corresponds to the total annual loss in elevation after the last rain event from the original DEM. The total sediment export or sediment yield, which is the amount of sediment leaving the catchment outlet, is evaluated by cumulating the net soil erosion on the cells within the catchment area. In this paper, the catchment erosion rate (ER) refers to the annual sediment yield (in t ha^{-1} year^{-1}).

2.3 | Climate scenarios

The climate scenarios, we adopted were based on daily rainfall projections under Coupled Model Intercomparison Project Phase 5 (CMIP5) simulated with the French Regional Climate Model CNRM-ALADIN 5.3, downloaded from the https://esg-dn1.nsc.liu.se/projects/esgf-liu/ platform for historical (H, 1985–2004) and future (F, 2040–2059) periods. Only the intermediate Representative Concentration Pathway (RCP) 4.5 emission scenario (Van Vuuren et al., 2011) was used because RCP4.5 was considered closer to a realistic balanced perspective and because the differences to the other RCP scenarios by 2050 were very small. Each of these two daily rainfall time series was first bias-corrected using a Quantile-Mapping statistical downscaling method (Gudmundsson et al., 2012; Panofsky & Brier, 1968; Sangelantoni et al., 2019) and then transformed into a 5-min time series using an 'analogue approach' based on the real rainfall dataset recorded between 1996 and 2006 in the meteorological station inside the catchment. The two downscaled rainfall time series showed annual averages of 814.9 and 765.0 mm year^{-1}, respectively for the current climate and future scenario, that is a 6.5% decrease (−49.9 mm year^{-1}). Mean annual USLE rainfall erosivity (R-erosivity) showed a decrease from 1683 MJ ha^{-1} mm h^{-1} for the period 1985–2004 to 1583 MJ ha^{-1} mm h^{-1} for the period 2040–2059, that is, 6.3% decrease.

2.4 | LUM scenarios

The catchment is representative of a classical grazing agro-ecosystem since pasture (i.e., combined intensive and extensive management), in its current configuration, represents 81.04% of the area. The cultivated surface is 7.03% (exclusively wheat) but, given the socio-economic context of the region and the global demographic growth, the future trend is supposed to show an increase in the cultivated areas. Based on a socio-economic study of the catchment for possible future agricultural innovations (see Pastor et al., 2022 for more details on all the socio-economic drivers taken into account, from local to global level), four narrative LUM scenarios with storylines were established for the horizon 2040–2060: a business-as-usual scenario, a market-oriented, a nature-oriented and one in line with the principles of sustainability. These scenarios have been created as part of a large approach for LU scenario development for Mediterranean areas as reported by Pastor et al. (2022). These were established according to two main driving concepts as reported in Figure 2, presenting a production axis in *y*, and an environmental protection axis in *x*. All the scenarios involve a diversification of agriculture through an increase in croplands (i.e., wheat and orchard) with a more or less strong intensity. The modulation along the environmental protection axis is done by adjusting land management, that is, conventional or conservative for crops, and intensive or extensive for grazing. Extensively managed grazing consists of a reduction in the number of livestock per square metre compared to intensive pasture, resulting in a reduction in soil compaction and an increase in vegetation cover. We did not consider changing the grazing schedule or the composition of the animal population, but only reducing grazing pressure (i.e., light grazing). In conventional wheat management, a deep ploughing is adopted, while in conservative management a shallow, less frequent tillage is preferred. Conventional orchards have deep ploughing twice a year, whereas in conservative management, the soil is grassed all over the year (with no tillage).

The business-as-usual scenario was based on the continuity of the current agricultural configuration. Extensive pasture and conventional wheat cultivation are maintained, while areas devoted to intensive pasture are partially converted to conventional wheat cultivation and orchards are introduced (3.68%) (Figure 3; Supporting Information Appendix B).

The market-oriented scenario aimed at maximising agricultural production by increasing production areas and modifying the organisation of the landscape. Extensive pasture is largely reduced (i.e., from 61.62% to 19.23%) in favour of intensive pasture (i.e., from 19.42% to

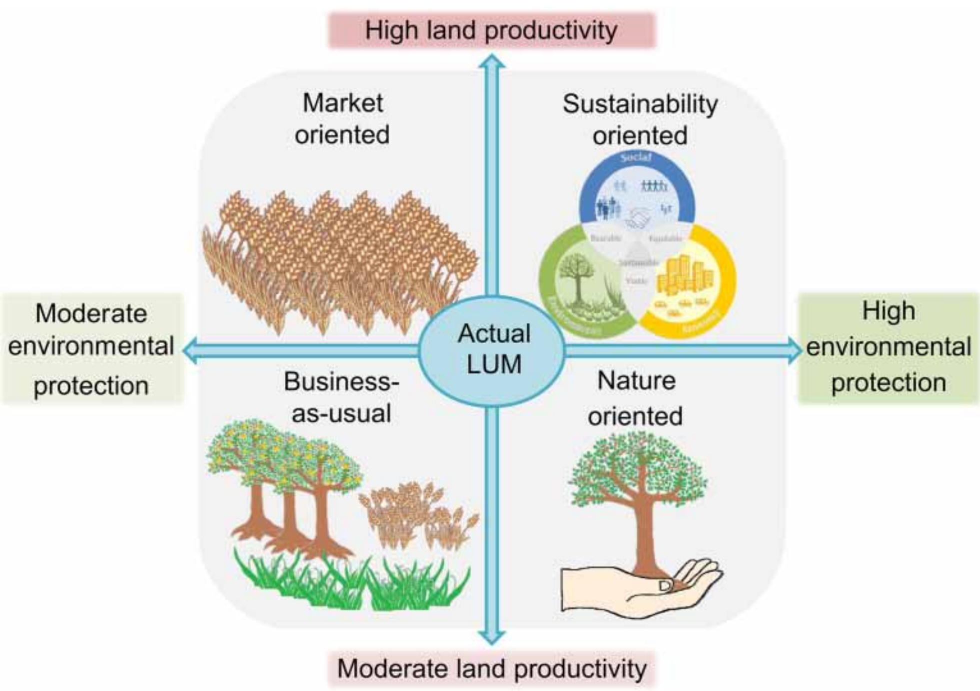

FIGURE 2 The four LUM scenarios used: business-as-usual (S1), market-oriented (S2), nature-oriented (S3) and sustainability-oriented (S4). [Colour figure can be viewed at wileyonlinelibrary.com]

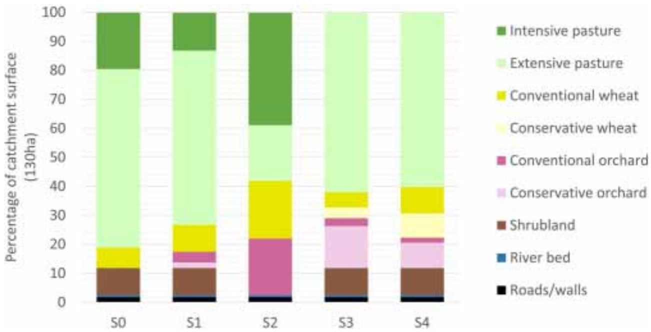

FIGURE 3 Distribution of LUM categories within the Cannata catchment for each scenario (S0 = current scenario; S1 = business-as-usual scenario; S2 = market-oriented scenario; S3 = nature-oriented scenario; S4 = sustainability oriented scenario). [Colour figure can be viewed at wileyonlinelibrary.com]

38.76%). Conventional wheat and orchard crops increased to 19.91% and 19.52%, respectively, and shrublands completely disappeared.

The nature-oriented scenario pointed at maximising soil protection and improving the ecological balance of the catchment by responding to environmental protection policies (i.e., according to the principles of the European Landscape Convention, Council of Europe, 2000). A total abandonment of the intensive pasture is made in favour of extensive pasture (61.91%) and conservative practices for wheat (3.69%) and orchard (14.50%).

The sustainability-oriented scenario aimed at a compromise between agricultural production and environmental conservation by the introduction of specific, local and ecological agricultural productions. The whole surface in pasture is extensively managed, and wheat and orchard crops are managed with a mix of conservative and conventional practices.

The LUM map for each scenario was drawn adopting land use feasibility rules based on landscape properties such as altitude, slope, soil type and exposition (Pastor et al., 2022), for example, wheat and orchard fields under conventional management were allocated to areas with the least steepness due to ploughing constraints, which is not the case for plots under conservative management (Figure 4).

2.5 | Model implementation

LandSoil parameterization for Cannata catchment consisted in defining a monthly calendar of the soil surface properties for each LUM category and soil type in current and future scenarios, and a monthly tillage schedule for each land use with their corresponding ploughing coefficient (Supporting Information, Appendix C). The current LUM is identified as scenario S0. Differentiation in pasture type (i.e., intensive vs. extensive) is done on the basis of the number of animals that can concentrate in specific areas, resulting in less roughness and ground cover between April and August for intensive compared to extensive. Conservative management of wheat and orchard influences the surface condition properties of soils, with changes in roughness, ground cover and crust development in certain periods of the year. Soil characteristics, that is aggregation stability, and crusting sensitivity are considered in the model input data by adopting the Le Bissonnais methodology (Le Bissonnais, 1996), which led to the soils of the area to be classified into two categories of reaction to the slaking action of water (Giuffrida, 2019) (Figure 1). Afterword, model calibration consisted in defining classes of infiltrability and sediment concentration based on surface conditions and on the characteristics of rainfall events. The calibration of these parameters was done on the basis of 30 rainfall events—that is, the most significant inside the 1996–2006 observation period—with runoff and sediment concentration recorded at the gauge station at the catchment outlet. The events were first discretized into three groups based on the rainfall amounts (i.e., low, medium and high). For each group, simulating the runoff and sediment yield, the parameters saturated soil infiltration and sediment concentration were adjusted so that the simulated values correspond to the observed values. Attention has been paid to ensure that the calibrated values remain within the range of values measured in the field by Licciardello, Aiello, et al. (2019). The parameters related to concentrated erosion were set to standard values as previously calibrated for similar Mediterranean soils in Ciampalini et al. (2012) because we did not dispose of the two separated components (rill and interrill) in the observations. Simulations over future conditions were made using the soil infiltration and sediment concentration values calibrated over the observation period (1996–2006).

2.6 | Simulation design and analysis

Various combinations for LUM and climate scenarios (Table 1) were simulated and the resulting erosion for each combination was compared to the baseline (S0-H) to quantify distinct and combined impact of changes for LUM and climate. Welch's two-sample *t*-test was used to determine whether the average ERs were significantly different between the combinations.

3 | RESULTS

3.1 | Model calibration under current conditions

The calibration of the simulated runoff and exported sediments provided satisfactory correlations with R^2 of 0.944 and 0.880, respectively, with linear regressions close to the 1:1 line. For the sediment export, an identified outlier on the right-hand graph of Figure 5 was removed from the calibration set, increasing the R^2 to 0.937. For each graph, the performance indicators depend largely on an extreme point. By removing this extreme point, conjointly with the outlier, the performance of the recalculated calibration resulted in a satisfactory simulated runoff with an R^2 of 0.872, and an R^2 of 0.731 for sediment export.

3.2 | Baseline erosion

The net soil erosion for current conditions (S0-H scenario) is shown in Figure 6. The average catchment ER is 2.15 t ha^{-1} year^{-1} (Figure 7). Out of 276.2 tons of sediments leaving the catchment each year,

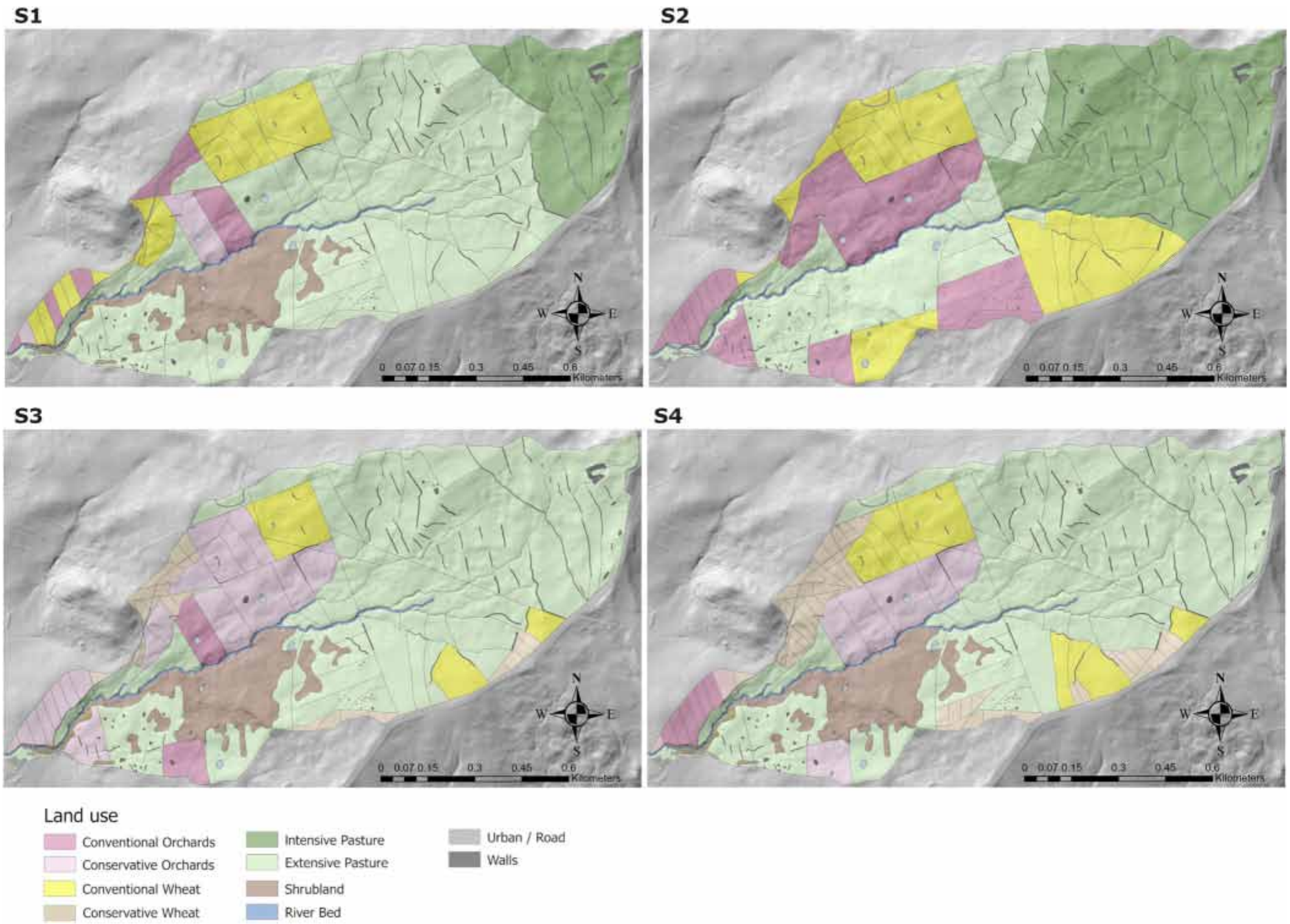

FIGURE 4 Cannata catchment LUM for scenarios S1 = business-as-usual scenario; S2 = market-oriented scenario; S3 = nature-oriented scenario; S4 = sustainability-oriented scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

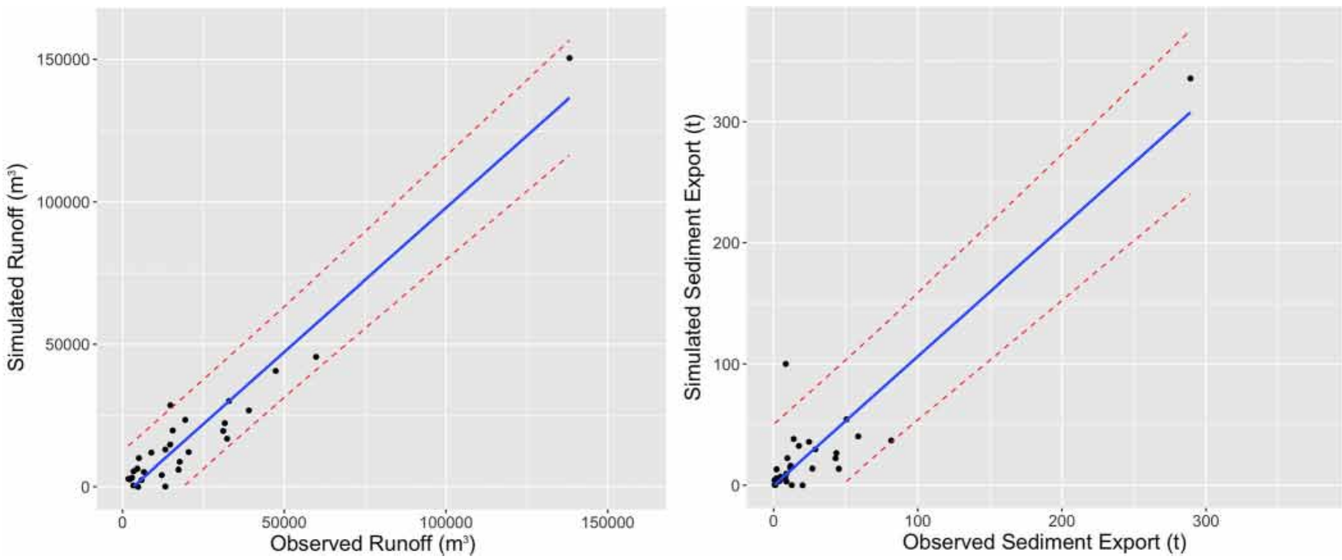

FIGURE 5 Simulated versus observed runoff (left plot) and total sediment exports (right plot) after the calibration process for the event monitored between 1996 and 2006 (n = 29). The blue lines represent the linear regression, and the red lines represent the 95% confidence interval. [Colour figure can be viewed at wileyonlinelibrary.com]

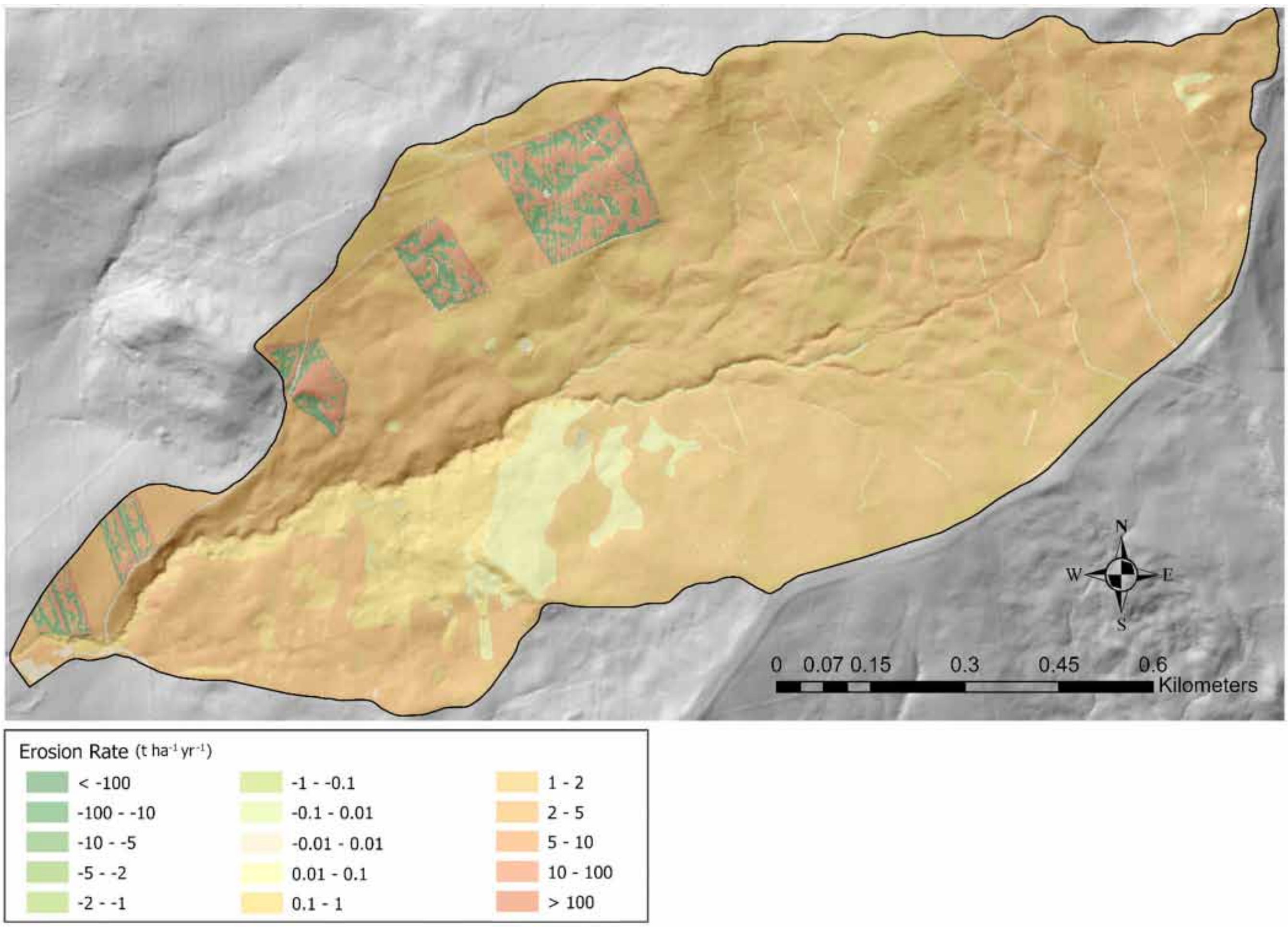

FIGURE 6 Baseline net soil erosion (t ha^{-1} year^{-1}) of Cannata catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

47.6% comes from extensive pasture, 21.4% from intensive pasture, and 12.6% from wheat cultivation. Net soil erosion shows moderate variations driven by slope and LUM, except for conventional wheat fields where an additional marked redistribution with extremes of erosion and deposition is found, explained by the predominance of intra-plot redistribution related to tillage. Plots under extensive pasture cause less erosion on a watershed scale than those under intensive management (2.03 and 2.36 t ha^{-1} year^{-1}, respectively). The difference between erosion on extensive and intensive grazing can be well observed at the two neighbouring surfaces because of the management of the pasture (e.g., in the North-East of the catchment area) or under the influence of other factors such as slope and catchment position respect to runoff accumulation (e.g., South-West). In general, as confirmed by Torresani et al. (2019), throughout field surveying and satellite data in Northeast Alps, grassland areas with high livestock density show more erosion than other land uses. Furthermore, Souther et al. (2019) found that intensive grazing tends to shift plant communities towards annual or invasive species, whereas moderate grazing promotes grazing ecosystem diversity. Cultivated plots have higher net soil erosion (i.e., 5.43 t ha^{-1} year^{-1} for conventional wheat) than non-cultivated plots (ranging from 0.44 t ha^{-1} year^{-1} for shrubland to 2.36 t ha^{-1} year^{-1} for intensive pasture), as soil tillage can significantly reduce plant cover in the winter period and, even if it temporarily promotes surface porosity, plots undergoing tillage make the soil more erodible (e.g., Cerdà et al., 2020). Erosion can be influenced by multiple factors, and over the effect of differences between LUM, here, plots show different net soil erosion modulated by slope or by type of soil. The plot's geometry (i.e., fragmentation, size, slope) also can deeply affect soil erosion, controlling landscape connectivity, thus runoff and erosion processes (e.g., Paroissien et al., 2010; Smetanová et al., 2019).

3.3 | Distinct impact of LUM and climate

3.3.1 | LUM scenarios

Simulating the LUM scenarios under the current climatic conditions (1985–2004) revealed different behaviours in averages (Figure 7). A low increase in catchment ER was found passing from the actual (S0) to the business-as-usual scenario (S1) (+6.0%). The market-oriented scenario (S2-H) induced an increase in ER of 57.2%

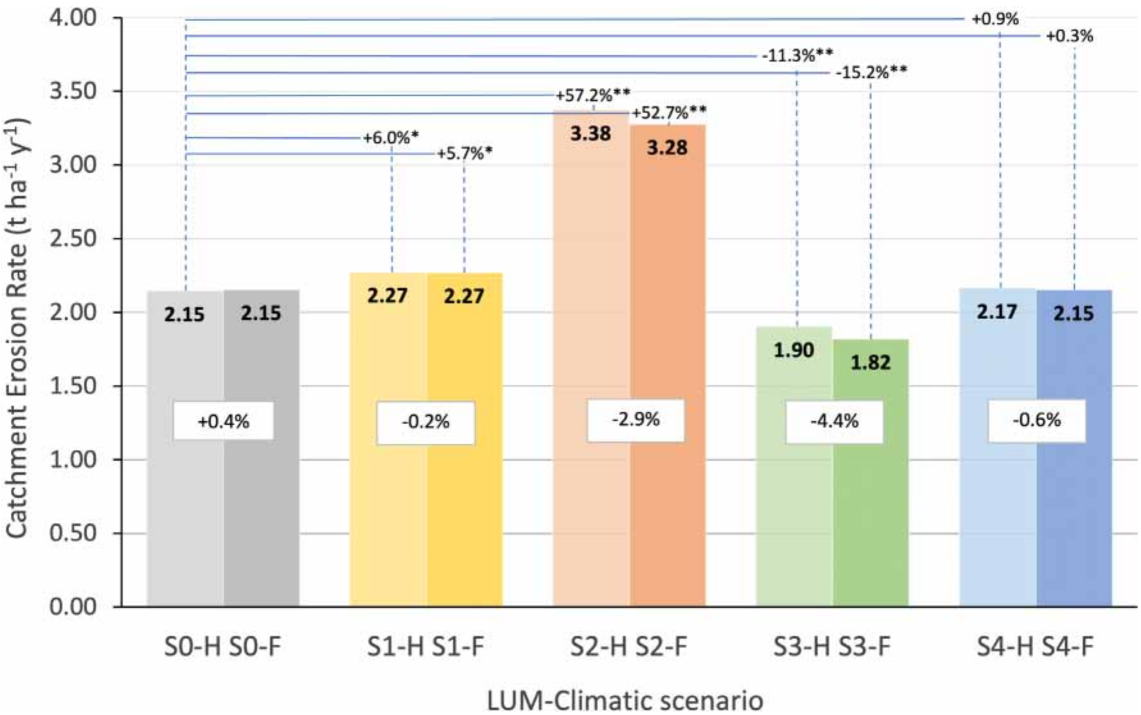

FIGURE 7 Catchment erosion rate (ER, in t ha^{-1} year^{-1}) according to different LUM scenarios (S0, S1, S2, S3, S4) for climate time series 1985–2004 (H) and 2040–2059 (F). The differences are indicated by connection lines between each specific scenario and baseline SH0. ** and * stands for significant difference at $p = 0.01$ and $p = 0.05$, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

compared to baseline reaching 3.38 t ha^{-1} year^{-1} on average. This value would threaten the sustainability of the soils in the study area, according to the estimate of Verheijen et al. (2009), qualifying this scenario as unfavourable. The sustainability-oriented scenario (S4-H) would substantially keep the same ER compared to baseline (+0.9%) while the nature-oriented scenario (S3-H) leads to a slight reduction (−11.3%). Such variations tested using a parametric Welch two-sample *t*-test, reveal (Figure 7) the increases for S1H-F and S2H-F are significant at $p < 0.01$ and 0.05, respectively, as well the decrease for S3 at $p < 0.01$.

Scenarios S3-H and S4-H suggest that a compromise in land management with increasing the cultivated area is possible (i.e., from 8.96% to 17.46% for wheat and from 17.2% to 10.49% for orchards) without a significant rise in ER as for S3-H or with a moderate increase in S4-H. Conservative management could reduce soil erosion compared to conventional management (e.g., Zhang & Nearing, 2005): scenario S4-H favours conservative farming management (70% of the cultivated area) and exclusively extensive pasture. These elements represent potential ways to preserve soil from erosion.

3.3.2 | LUM categories

The total sediment exported from the catchment (t year^{-1}) is first governed by the relative LUM categories of each scenario (Figure 8a). For the S1-H, S3-H and S4-H scenarios, extensive pasture, which accounts for about 60% of the catchment area, produces most of the sediment exports (119.57, 118.65 and 113.67 t year^{-1}, respectively). Conversely, shrubland representing 9.36% of the catchment, a smaller but still significant surface, presents a very low contribution to total sediment exports (0.51, 0.60 and 0.49 t year^{-1}). Wheat crops, with surfaces ranging from 9.3% to 19.9% (S3 and S2) generate sediment exports from 46.0 to about 122.6 t year^{-1}, while orchards with surfaces from 5.6% to 19.5% (S1 and S2) are still among the land use with considerable sediment production (S1 and S3, 30.5–55.8 t year^{-1}).

The specific contribution of each LUM category to ER is shown in Figure 8b. The contribution of intensive pasture in scenario S1-H is lower (2.28 t ha^{-1} year^{-1}) than of wheat and orchards under conventional management (6.07 and 4.69 t ha^{-1} year^{-1}, respectively). In S2-H, the scenario with the highest ER, the contribution of conventional orchards, representing only 19.5% of the catchment area, is particularly high (5.32 t ha^{-1} year^{-1}). In the S3-H scenario, the conventional orchard (2.7% of the catchment) has a higher contribution (4.78 t ha^{-1} year^{-1}) than the conservative orchard (2.09 t ha^{-1} year^{-1}), and conventional wheat (4.31 t ha^{-1} year^{-1}) than conservative (3.46 t ha^{-1} year^{-1}). In the S4-H scenario, orchards contribute to 1.78 t ha^{-1} year^{-1} under conservative management and 6.75 t ha^{-1} year^{-1} under conventional management.

In general, net soil loss and soil exportation under LU scenarios depend on (1) the extent of each land use within the catchment, (2) the choice of the soil crops (i.e., ERs, in general, follow the ranking: wheat > orchard > pasture) and (3) the crop management (i.e., erosion in conventional-wheat/orchard > conservative-wheat/orchard). The hierarchy in ERs for some specific land use may sometimes be

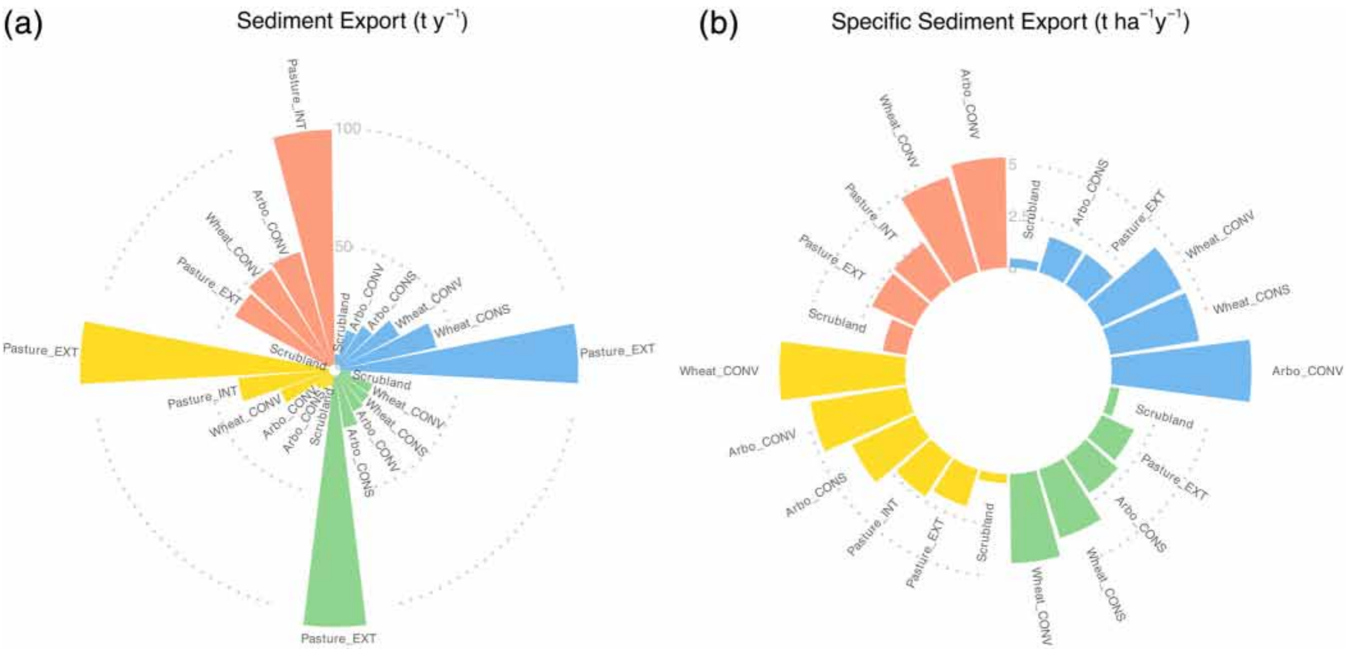

FIGURE 8 Contribution of each LUM category to (a) sediment exports (t yr^{-1}) and (b) ER (t ha^{-1} year^{-1}) for each scenario (S1 in yellow, S2 in red, S3 in green and S4 in blue) with the 1985–2004 climate time series. [Colour figure can be viewed at wileyonlinelibrary.com]

unexpected due to the spatial allocation rules that have been adopted. Indeed, sometimes conservative management has a little higher specific erosion value than conventional management for the same land use (e.g., wheat in S4-H). This is because conventional management practices have been preferentially assigned to the largest and flattest fields in the watershed due to ploughing constraints, while conservative management is located on steeper, often small fields downstream of the catchment.

These results illustrate the fact that the impact of a change in LUM is difficult to anticipate due to the complexity of the drivers and their combination.

3.3.3 | Climate scenarios

The comparison of the simulations for the historical and future rainfall time series shows little variation in sediment export rates (Figure 7). The difference in ER for each LUM under the two climate scenarios, tested using the Welch two-sample *t*-test, showed rejection for a two-sided dataset in all the combinations (Figure 7). Very little difference is observed for S0, S1 and S4 scenarios with approximately the same values between current and future scenarios (+0.4, −0.2, −0.6%), while slight decreases are observed in S2 and S3 (−4.6%, −3.9%), still not significant but, consistent with the decrease we found in the R-erosivity for the future climatic scenario. Such a difference in response between S0–S1–S4 and S2–S3 is supposed to be due to the induced variation in catchment LU patterns, giving a stronger response to the R-erosivity decrease in S2, S3 compared to the S0–S1–S4.

4 | DISCUSSION

4.1 | Combined impact of LUM and climate

Among all the scenarios, S2 represents the most unfavourable, resulting in an increase in erosion of 52 and 57% for the two climatic scenarios compared to the current S0-H. S4 appears to be a good compromise as it increases crop areas cultivated in wheat and orchards from 7% to 28% of the watershed area while preserving catchment ERs at the same level as the current scenario (S0). Such agricultural diversification is achieved mainly via conservative management of crops and extensive management of pasture. As a result, S4 is rather conservatively managed with 17.12% of the catchment (8.37% wheat and 8.75% orchard). Conventional crops, which ensure good agricultural production, represent 10.83% of the catchment area with 8.37% wheat and 1.74% orchard. S3 instead, gives a decrease in erosion (−11% to −15%) because of the large use of conservative surfaces (80.1%) while still maintaining a considerable total surface for crop production (26.16%). Controlled ER as in S4 and S3 are in line with other simulations that have observed substantial soil preservation and erosion reduction achieved by testing increased percentages of grass cover in Iranian rangelands (Zakeri et al., 2020) or reduced grazing pressure in the Mediterranean island of Crete (Panagopoulos et al., 2019).

The results obtained in this study highlighted the low direct impact of climate change on soil erosion, which is consistent with the very limited increase in extreme precipitation occurrence in future trends for the southern Mediterranean, including Sicily (Tramblay & Somot, 2018). They also confirm the effectiveness of land use and land cover management as a lever for combating soil degradation in a context of climate change in the Mediterranean region, a result already evidenced in other Mediterranean agro-ecosystems than the one tested in this article (e.g., Choukri et al., 2020; David et al., 2014; Paroissien et al., 2015; Pastor et al., 2019; Serpa et al., 2015).

4.2 | LUM—A lever to improve agricultural attractiveness

With the aim to inspect agricultural productivity and soil protection, in Figure 9, the results are represented adopting the two main axes conceived in creating the LUM scenarios, a productive axis, vertical, and a protection axis, horizontal. Then, for each scenario, the catchment ERs are plotted, against the percentage of the cultivated crop surface (i.e., Y, production axis) versus an index of soil protection (i.e., X, conservation axis) calculated as the inverse of the logarithm of the ratio of the area managed with conventional or intensive practices to the area with conservative or extensive practices.

We observe that the LUM S0 evolves towards scenario S1 increasing the cultivated surfaces from 7.03 to 14.92% while conserving an intermediate protection index. The S1-H scenario shows an increase in erosion from S0-H of 6.0%, which is slightly less marked under the influence of climate change erosion (S1-F, +5.7%) (Figure 7). As expected, S2 shows maximum cropped surfaces (39.43%, i.e., high crop productivity), low protection index and maximum erosion.

Along an ideal transition from S2 to S4, the cultivable area is reduced to 27.95% leading to a limited erosion close to the S0 (2.15 vs. 2.17 t ha^{-1} year^{-1}) but with a larger cropped area. In S4, the catchment ERs (2.17–2.15 t ha^{-1} year^{-1}) are in line, for instance, with the average values for arable in Europe (i.e., 2.46 t ha $^{-1}$ year^{-1}, Panagos et al., 2015). Even if tolerable soil loss is still a controversial subject, the catchment ERs for S4 remain within the range of values suggested by the Environmental European Agency (2–4 t ha^{-1} year^{-1}; EEA, 2022, p. 146).

In scenario S3, instead, the protection, due to the large conservative crops (18.18%), is maximum, and the erosion is the lowest (1.90 and 1.82 t ha^{-1} year^{-1}), with a cultivated area comparable to S4 (26.16% vs. 27.95%), still with higher productivity than in S1-H but lower erosion.

A good compromise for farmers lies in scenario S4, where the cultivated area is high but with limited erosion as in S1, and with fewer constraints on crop management and higher crop productivity than in S3.

The result of S4, similarly to the S3 scenario, responds to the adoption of fully extensive grazing in association with large surfaces of conservative orchards and wheat, while increasing the cultivated area.

Similar results, such as reduced susceptibility to erosion in orchards, have already been observed by van Oudenhoven et al. (2015), which in a global analysis including 25 studies for semi-arid to sub-humid rangelands verified that the land management with the introduction of tree plantations in pastures conjointly with the discontinuation of grazing can successfully drive towards less soil degradation when intensive exploitation is avoided.

The impact of the effectiveness of reducing grazing on soil erosion has also been verified and confirmed in the Mediterranean context. For instance, Pulido et al. (2018), in southwest Spain, found an effect on soil surface properties due to water processes (i.e., resulting in bare soil and compaction) for paddocks with animal load rates above one equivalent unit of livestock per hectare. Kosmas et al. (2015), simulating the effect of grazing intensity and land use changes over the last half-century in the Creta Island, found an increase of soil

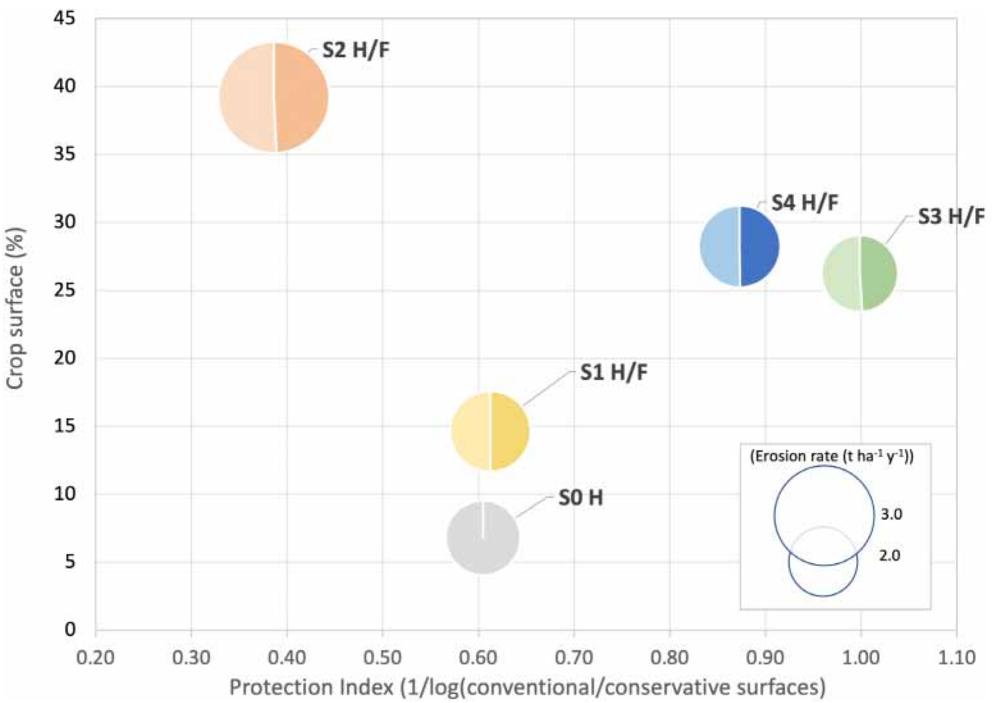

FIGURE 9 Catchment erosion rates (t ha^{-1} yr^{-1}) of the different scenarios represented along a crop production axis (*y*-axis, % of crop surfaces) and the protection axis (*x*-axis, protection index evaluated as 1/log [conservative/conventional surfaces]). [Colour figure can be viewed at wileyonlinelibrary.com]

ERs in the mid-1980s–2010 period due to the reduction of vegetation cover by overgrazing. Kizos et al. (2013), studying the socio-economic effects in an insular context of the eastern Mediterranean (Lesvos, Greece) since early 1960s, observed a consequential loss of traditional ecological knowledge in the transition from a classical agrosilvopastoral system to a market economy based on animal production.

Therefore, it can be argued that, in such a context of global change, mountainous areas, which are somewhat abandoned, offer the possibility of greater attractiveness by diversifying agricultural production with crops while adapting agricultural practices. This may be the key to a sustainable revitalization of the mountainous hinterlands of the Mediterranean.

4.3 | Future works

Understanding the future of Mediterranean mountain rangelands is a major challenge, as this environment is a highly complex socio-ecosystem. One of the original features of our approach has been to take account of socio-economic considerations in the establishment of LUM scenarios, and then simulate their impact using distributed physically-based modelling. A challenging factor in improving this approach is to be able to expand the number of trajectory modalities to be explored. In this paper, we studied the impact of agricultural diversification combined with the management of grazing resources by alleviating grazing pressure through a reduction in the number of livestock per hectare (i.e., continuous light grazing). However, it would be interesting to test in future works other enhanced grazing management systems that have proved to be a highly effective approach for managing grazing lands sustainably. For example, Teague and Kreuter (2020) have shown that Adaptive Multi-Paddock (AMP), which consists of short periods of grazing with high density of animals within paddocks, could provide superior ecosystem and profitability outcomes than the continuous light grazing tested in this paper.

A more comprehensive investigation of the trade-offs involved in the sustainable development of Mediterranean mountain pastures requires a holistic modelling approach that combines biophysical and socio-economic behaviour. Recent efforts proposed by Martínez-Valderrama and Ibáñez Puerta (2023), although an important step forward, still need to be pursued to increase our ability to predict these complex ecosystems, especially at local scale where site-specific conditions need to be taken into account. In our opinion, one possible strategy is to develop a holistic approach that includes a sufficiently detailed description of the biophysical processes, both in terms of the nature of the processes and their description and spatialisation, to be relevant for implementation on local sites.

5 | CONCLUSIONS

In this study, we examined the effects of climate and land use management scenarios on soil erosion in a Mediterranean mountainous catchment dominated by pasture lands. To our knowledge, it was the first time that LUM scenarios incorporating environmental and socio-economic behaviour were simulated using a distributed process-based model to explore the impacts of plausible global change trajectories in a very detailed way in this type of ecosystem. Simulations conducted on a case study located in Sicily using the LandSoil model showed that soil erosion will not be significantly affected by climate change (i.e., −1.78% of erosion on average). Under current climate and compared to the baseline, LUM scenarios reported an increase in erosion for the business-as-usual (S1, +6.0%), market-oriented (S2, +57.2%) and sustainability-oriented (S4, +0.9) scenarios, respectively, while the nature-oriented scenario led to a slight reduction in erosion (S3, −11.3%). Our results confirm the effectiveness of land use and land cover management as a lever for combating soil degradation in a context of climate change, as already demonstrated for other Mediterranean agro-ecosystems. They also demonstrate that it is possible to increase the attractiveness of mountainous areas dominated by pasture by diversifying agricultural production with crops while maintaining soil protection at an acceptable level through the adaptation of agricultural practices and management. The LUM trajectories tested in this study could be useful for guiding incentive policies towards future sustainable grazing management systems in Mediterranean uplands. However, other sustainable trajectories are undoubtedly possible and any means of facilitating more holistic studies into the future of these ecosystems should be encouraged.

AUTHOR CONTRIBUTIONS

Conceptualization: Feliciana Licciardello, Damien Raclot and Rossano Ciampalini. *Data provision*: Feliciana Licciardello. *Funding acquisition*: Damien Raclot. *Scenarios elaboration*: Amandine Valérie Pastor and Feliciana Huard. *Simulation and modelling*: Laurène Marien, Emanuela Rita Giuffrida and Rossano Ciampalini. *Writing original draft*: Laurène Marien, Rossano Ciampalini and Damien Raclot. *Writing review and editing*: all co-authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Laurène Marien https://orcid.org/0000-0003-1445-2940
Emanuela Rita Giuffrida https://orcid.org/0009-0009-7453-5378
Damien Raclot https://orcid.org/0000-0002-6445-6168

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SUPPORTING INFORMATION

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