



# Impacts of agricultural intensification on soil erosion and sustainability of olive groves in Alentejo (Portugal)

A. A. Rodríguez Sousa · J. Muñoz-Rojas ·  
C. Brígido · S. A. Prats

Received: 31 January 2023 / Accepted: 30 April 2023  
© The Author(s) 2023

## Abstract

**Context** Olive groves are key features of Iberian Mediterranean landscapes. With the intensification of olive grove production, some negative environmental impacts on soils must be considered to achieve farm sustainability.

**Objectives** To estimate, theoretically and empirically, soil erosion in olive groves of Alentejo (Portugal) considering different planting densities and soil managements (i.e. conventional, integrated, organic), and related impacts on soil loss and farm sustainability.

**Methods** Soil erosion was empirically calculated using sediment traps. Soil loss was modelled using the Universal Soil Loss Equation (USLE) model. The impact of erosion on farm sustainability was assessed by simulating future projections to 100 and 500 years. **Results** An overestimation of theoretical erosion rates for all olive management models compared to the empirical results was observed. Plant cover strongly contributed to reduce soil loss. Temporal simulations based on experimental data showed a longer sustainability of intensive groves than expected according to theoretical values.

**Conclusions** Despite the negative impacts of intensive agriculture, this study highlights that it is essential to consider soil management impacts on erosion, an aspect that influences farm sustainability, regardless of planting density. Future studies should expand our experiments across a wider sample and locations of olive groves, to better discern how olive sustainability is impacted by different agricultural management options and decisions.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10980-023-01682-2>.

A. A. Rodríguez Sousa (✉)  
Department of Statistics and Operations Research, Faculty of Mathematical Sciences, University Complutense of Madrid, Pl. De las Ciencias 3, 28040 Madrid, Spain  
e-mail: antonr05@ucm.es

A. A. Rodríguez Sousa · C. Brígido · S. A. Prats  
MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Instituto de Investigação e Formação Avançada, Universidade de Évora, Pólo da Mitra, Ap. 94, 7006-554 Évora, Portugal

A. A. Rodríguez Sousa · C. Brígido · S. A. Prats  
Universidade de Évora, Largo dos Colegiais 2,  
7004-516 Évora, Portugal

J. Muñoz-Rojas (✉)  
MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Departamento de Geociências, Universidade de Évora, Pólo da Mitra, Ap. 94, 7006-554 Évora, Portugal  
e-mail: jmrojas@uevora.pt

**Keywords** Agro-ecosystems · Land management · Semi-arid agriculture · Scenario planning · Simulation and modelling

## Introduction

The European Union hosts circa 175 million hectares (M ha) of Land in Agricultural Use (LAU), with 5 M ha devoted to olive groves (EUROSTAT 2021). These groves occupy more than 2.90 M ha in the Iberian Peninsula (Fregapane and Salvador 2019; Rodríguez Sousa et al. 2020). Olive groves are multifunctional farming and land-use systems, contributing, through multiple ecosystem services (ES, considered the benefits that an ecosystem brings to society), to human well-being and resulting in social, economic and environmental benefits (Fleskens et al. 2009). In the Iberian Peninsula olive groves occupy 3 M ha, specifically exceeding 350,000 ha in Portugal, forming heterogeneous landscapes (Fraga et al. 2020; Villa et al. 2020; Rodríguez Sousa et al. 2021). Olives and olive oil in Portugal have lately become an emergent sector, economically contributing to 1.36% of the national farm income; promoting the social dimension linked to the generation of employment; and typically associated with a positive environmental dimension, potentially hosting abundant biodiversity (Pizzolotto et al. 2018; Rey et al. 2019; Santos et al. 2007a, b). Olive oil production in Portugal has risen up to 270,000 t of oil (INE 2022a, b). In addition to provisioning ES (i.e. food production), olive groves also deliver regulating ES (i.e. atmospheric carbon sequestration or erosion mitigation) (Maldonado et al. 2019; Rodríguez-Entrena et al. 2012). Finally, these farming systems also deliver multiple and valuable cultural ES, contributing to rural development through oleo tourism (D'Auria et al. 2020).

51% of the olive-growing area in Portugal is in Alentejo (Southern Portugal) (INE 2022a). The proximity of the Alqueva reservoir (surface area of 250 km<sup>2</sup> and capacity of 4150 hm<sup>3</sup>) allows a great source of water to regional agriculture, with 53.26% of olive groves benefitting from irrigation infrastructures, with the remaining 46.74% being rainfed (Rodríguez-Cohard et al. 2019; Fraga et al. 2020). To respond to the social demands of the Portuguese society towards agriculture about a stable food supply, extensive olive groves are undergoing a gradual intensification process to maximize their yields in the long term (EC 2020).

Olive intensification is directly associated with an increase in tree density (Pastor et al. 2007; AEMO 2020). By applying this criterion, highly-intensive

(1000–2000 trees ha<sup>-1</sup>) and intensive groves (i.e. 200–800 trees ha<sup>-1</sup>) in Alentejo account for 63.80% of the olive-growing area (responsible for 75% of olive production) (INE 2022a). Intensive groves are affected by widespread perceptions of negative environmental connotations, related to the fact that many of them have applied the removal of herbaceous under-cover, which leads to a greater risk of erosion (Caraveli 2000; de Graaff et al. 2010). However, several studies have shown how planting density is a secondary agronomic character that does not necessarily determine farm sustainability (i.e. lifespan), a concept closely linked to landscape ecology through the adoption of agricultural management models that guarantee the socio-economic profitability of the systems, along with a minimum environmental impact (Rodríguez Sousa et al. 2019a; Camposeo et al. 2022). In contrast, soil management seems to be a key determinant of farm sustainability (Metzidakis et al. 2008). Thus, olive groves with high planting densities can present different forms of soil management. Intensive and highly-intensive olive groves, as well as extensive groves, can present a conventional soil management, where the use of chemical fertilizers and machinery is allowed; integrated, where the addition of chemical inputs is controlled; or organic, where only natural fertilizers can be applied (De Gennaro et al. 2012; Romero-Gámez et al. 2017). Each one of these models applies different strategies to control soil vegetation, ranging from the maintenance of the original grass vegetation to removing, partially or completely, plant cover. Maintenance of herbaceous plant cover is an agro-environmental measure that enhances soil fertility and minimize soil losses (Zuazo and Pleguezuelo 2009). In addition, organic groves may be managed using a biodynamic approach, a circular-economy system where only fertilizers from the farm itself are allowed, guaranteeing their protection against cross-contamination from neighboring farms (Santoni et al. 2022).

Considering the increasingly rapid expansion of olive groves in Portugal, numerous studies have been carried out looking at the negative repercussions of soil erosion on agricultural productivity (Rodríguez Sousa et al. 2021, 2022), and on how different managements models can help increase or mitigate soil loss in crops (Guerrero-Casado et al. 2021). In this sense it is essential to quantify the implications of increasing the tree density and the impact of soil

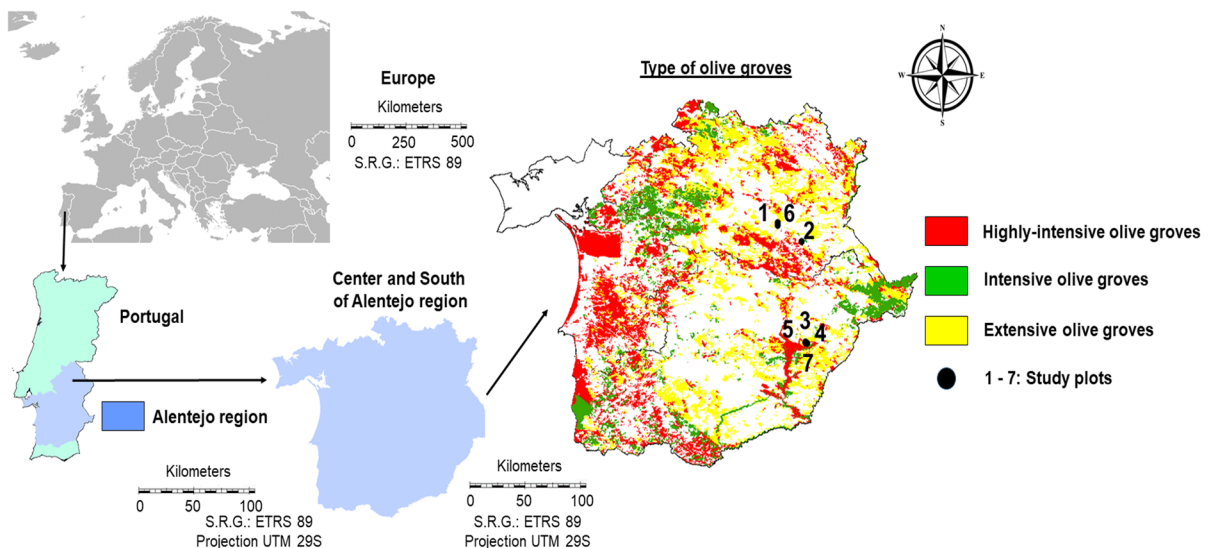
management practices on erosion. Soil erosion is a key threat to farm sustainability due to the impacts on soil fertility and agricultural productivity (de Graaff et al. 2010). The main aim of this study is to evaluate, through the combination of theoretical models and empirical measurements, how different management practices (i.e. conventional, integrated and organic) in olive groves with variable planting density can modify soil loss rates, affecting farm sustainability. The specific objectives were: (a) to estimate, empirically, the annual erosion of olive groves in Alentejo, in 7 experimental plots; (b) to calibrate according to the Universal Soil Loss Equation (USLE) the potential for erosion of each model of olive grove management and check the degree of adequacy between the model and empirical data; and (c) to implement a simulation model that evaluates how erosion affects the medium and long-term sustainability (lifespan) of crops through 100- and 500-year time projections.

## Methods and data processing

### Study area

Central and Southern Alentejo (NUTS-3 administrative units, which in Portugal are termed as Districts) was chosen as the study area, where olive

groves exceed 170,000 ha (INE 2022a). To conduct our empirical research 7 study plots were selected to monitor erosion in the field for one year. This region is characterized by a Mediterranean climate, with an average temperature between 9 and 24 °C and a rainfall of up to 550 mm (Fraga et al. 2020). Olive groves in Alentejo are mainly located over igneous (granite) and metamorphic rock parent materials (schist) with 20 to 150 cm deep and clay to loamy texture, at altitudes of 200–600 m above sea level (m.a.s.l.) (Rodríguez Sousa et al. 2021). From a planting density point of view, a distinction is widely accepted between extensive (<200 trees ha<sup>-1</sup>), intensive (200–800 trees ha<sup>-1</sup>) and highly-intensive groves (1000–2000 trees ha<sup>-1</sup>) (Copernicus Land Monitoring Service 2018; Fig. 1). As aforesaid, each of these types can be managed conventionally, integrated or organically (with only a minority of plots yet under biodynamic management). Although near 47% of the olive groves in Alentejo are rainfed, all management models allow the incorporation of irrigation, being mostly through deficit irrigation (i.e. addition of up to 1500 m<sup>3</sup> ha<sup>-1</sup> in times of water stress) (Pérez et al. 2010).



**Fig. 1** Location of Central and Southern Alentejo (Portugal) and the study plots, specifying the types of olive groves according to planting density: extensive, intensive or highly-intensive

## Characterization of the study olive groves

The seven olive groves of our study, corresponded to 5 different management models: (a) highly-intensive groves managed as integrated or organically (biodynamic); (b) intensive groves managed as integrated or organically; and (c) extensive and organic olive groves (Table 1). All crops were irrigated, except the extensive grove, which presented 100% vegetation cover, while the remaining ones presented cover percentages between 15 and 57%. Only two groves with highly -intensive and intensive densities used herbicides to control vegetation. While three groves (i.e. highly-intensive and intensive olive groves) used plowing along the tree rows, 2 of the same groves, along with another one with intensive and organic management also cut the grass in the interrow. The plots showed variable slopes (between 12.28 and 23.09%). The different structural characteristics of the groves resulted in high variability in terms of the risk of erosion, thus serving the sample units as a reference to determine whether soil management is a conditioning factor for erosion.

### Erosion measurements and soil analysis

Soil erosion was monitored during 2021–2022 implementing 3 to 4 plots in each of the seven olive groves in Table 1 (i.e. final sample size of  $n=22$  plots). Soil loss was quantified through the implementation of a sediment collection trap (plot) designed to retain soil particles removed from the crop through erosion (i.e. laminar and rill erosion) (Lima-Cueto et al. 2018).

Each sediment fence (3–4 m length, 1–2 m width, 40–50 cm high) consisted in a collector that was fixed to the ground using a geotextile fabric, wooden stakes and nails (Prats et al. 2016). These traps allowed the water to settle and the sediments to deposit (Prats et al. 2016). The installation was completed in May of 2021 (Fig. 2), the quantification of the sediments followed on a monthly basis or immediately after each heavy rainfall event for a one-year period. The amount of wet sediments in the traps was collected and weighed in the field, being able to determine dry soil losses in each sampling time after determine the dry weight (de Graaff et al. 2010; Gómez et al. 2009, 2018).

In each grove, three soil samples were taken using a metal core of 5 cm height (141.37 cm<sup>3</sup>), to determine soil physical parameters (stone content, dry bulk



**Fig. 2** Design of one of the sediment collection traps implemented in the experimental olive grove in Alentejo (Portugal)

**Table 1** Experimental olive groves numbered according to Fig. 1, specifying the olive tree density (trees ha<sup>-1</sup>), soil management, slope (°/%), and their main management practices: presence/absence of irrigation, herbicides, plowing or herbaceous cutting (cutting)

Grove number	Type of olive grove		Main management practices					
	Tree density (trees ha <sup>-1</sup> )	Soil management	Slope (°/%)	Irrigation	Vegetation strip cover (%)	Herbicides	Plow lines	Cutting
1	Highly-intensive (1925)	Integrated	7°/12.3%	Yes	24.1	Yes	No	No
2	Highly-intensive (1186)	Organic (Biodynamic)	7°/12.3%	Yes	56.1	No	Yes	Yes
3	Intensive (272)	Integrated	13°/23.1%	Yes	19.3	Yes	No	No
4	Intensive (284)	Organic	9°/15.8%	Yes	15.9	No	Yes	No
5	Intensive (341)	Organic	7°/12.3%	Yes	37.1	No	Yes	Yes
6	Intensive (339)	Organic	8°/14.1%	Yes	18.7	No	No	Yes
7	Extensive (104)	Organic	12°/21.3%	No	100	No	No	No

density, soil texture and soil organic matter). Samples were firstly dried to obtain their dry bulk density value (Eq. 1, Gómez et al. 2009):

$$DBD = \frac{DSW}{V_c}, \quad (1)$$

where  $DBD$ ; dry bulk density ( $\text{g cm}^{-3}$ );  $DSW$ ; dry soil weight of the sample (g);  $V_c$ ; core sample collection volume ( $\text{cm}^3$ ).

After sieving the soil samples with a 2 mm mesh, the stone content was determined, and the fine fraction was used to obtain the soil texture following the Bouyoucos method (sands: particles of 2 mm–50  $\mu\text{m}$ ; silts: 50–2  $\mu\text{m}$ ; clays: particles smaller than 2  $\mu\text{m}$ ) (Bouyoucos 1962). Existing mapping was used to estimate the average soil depth of each of the plots (DGT 2022), and the soil weight per unit area was estimated according to Eq. 2 and 3 (soil weight corresponding only to the fraction lower than 2 mm) (Gisbert Blanquer et al. 2012):

$$W = 100 \cdot Sd \cdot DBD, \quad (2)$$

$$W < 2 \text{ mm} = (W \cdot (100 - \%Stones)) \cdot 100^{-1}, \quad (3)$$

where  $W$ ; soil weight ( $\text{t ha}^{-1}$ );  $Sd$ ; soil depth (cm);  $DBD$ ; dry bulk density ( $\text{g cm}^{-3}$ );  $W < 2 \text{ mm}$ ; soil weight for the soil fraction lower than 2 mm ( $\text{t ha}^{-1}$ );  $\%Stones$ : representativeness of soil particles larger than 2 mm.

Finally, we estimated the organic carbon content of the soil samples through an indirect colorimetric method using  $\text{K}_2\text{Cr}_2\text{O}_7$ , the organic matter content, as shown in Eq. 4 (Aranda et al. 2011):

$$OM = 1.724 \cdot [C], \quad (4)$$

where  $OM$ ; soil organic matter content (%); 1.724; Van Bemmelen's factor for conversion of organic carbon to organic matter;  $C$ ; organic carbon content of sample (%).

### Modelling soil erosion

Soil erosion due to surface processes (i.e. laminar and rill erosion) was estimated using USLE model (Wischmeier and Smith 1960; Kinnell 2010). This was done for all possible types of olive groves in Alentejo (Portugal) (i.e. highly intensive, intensive and extensive groves managed via conventional, integrated

or organic models). To cover the large variability in terms of olive grove management systems, different criteria were used to calibrate each USLE factor (Eq. 5) specifically for the study area:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P, \quad (5)$$

where  $A$ ; potential erosion ( $\text{t ha}^{-1} \text{ year}^{-1}$ );  $R$ ; rainfall erosivity ( $\text{J ha}^{-1}$ );  $K$ ; soil erodibility ( $\text{Mg J}^{-1}$ );  $LS$ ; length and degree of slope (dimensionless and in degrees or %);  $C$ ; soil vegetation cover (dimensionless);  $P$ ; implementation of soil conservation agricultural practices (dimensionless).

For the calibration of the R-factor, the specific criteria, that had previously applied in Alentejo by Santiesteban et al. (2005) and Rodríguez Sousa et al. (2021, 2022), were followed, where a value of  $95 \text{ J ha}^{-1}$  was assumed. The K-factor was calculated using the criteria of Gisbert-Blanquer et al. (2012), estimating this parameter according to soil texture, organic matter content, structure and permeability (these values were estimated according to the nomograms of Wischmeier et al. (1971) and the criteria of Auerswald et al. (2014), assuming general values of 2 and 4 respectively).

Considering that the steeper the slope, the greater the risk of erosion, the criteria of Moreira-Madueño (1991) was adapted to estimate erosion equivalently with the experimental plots, generating 4 erosive intervals: (a) moderate slopes up to 10% (5.71 degrees); (b) slightly severe slopes up to 15% (8.53 degrees); (c) severe slopes up to 20% (11.31 degrees); and (d) very severe slopes up to 25% (14.03 degrees). The LS factor was estimated following the criteria of Renard et al. (1997) and Eqs. 6–7 (LS factor was estimated through the multiplication of L and S subfactors).

$$L = (Slope \cdot 22.13)^{(\sin Slope \cdot \sin 5.143) \cdot (\sin Slope^{0.8} + 0.56)^{-1}}, \quad (6)$$

$$S = (16.8 \cdot \sin Slope - 0.5), \quad (7)$$

where  $L$ ; slope length dependent subfactor (dimensionless);  $Slope$ ; slope of the territory (constant assumption of 100 m);  $\sin Slope$ : sine of the slope of the territory in degrees;  $S$ ; subfactor corresponding to the magnitude of the slope (dimensionless).

The C Factor, according to Gómez et al. (2003) and Russo et al. (2016), can be modified according to: (a) the planting frame, higher in extensive groves

(7×7 m or 8×8 m), while in intensive and highly intensive groves such frames are reduced to 6×5 m and 2×2 m respectively, resulting in an increase in the C-factor; (b) tree crown radius, related to tree age, a parameter that acquires higher values in extensive groves, with crown radius of 2.5 m, contributing to minimize C-factor. In intensive and highly intensive groves, olive trees are usually younger, with crowns of 1.5 m (AEMO 2020; Romero-Gómez et al. 2017), resulting in higher values of the C-factor; and (c) the presence of herbaceous plant covers that are very common in extensive groves, being more patchy in those groves managed conventionally, more dense and continuous in integrated groves, and presenting a total cover in organic agriculture (reducing C-factor and erosion) (Zuazo and Pleguezuelo 2009). Highly intensive and intensive groves under integrated or organic management maintain the soil vegetation, but conventional groves partially remove the vegetation (Metzidakis et al. 2008). According to Rodríguez Sousa et al. (2019a) C-factor values of 0.25, 0.16 and 0.06 were used for, respectively, extensive groves with conventional, integrated and organic managements. The intensive and highly-intensive conventional groves C-factor was 0.41 and 0.50 (Rodríguez Sousa et al. 2022). Finally, P-factor varies between a range of 0 and 1, but the absence of any structural characteristic that minimize the impact of tillage practices led to the selection of a conservative value of 1 (Sánchez-Escobar et al. 2018).

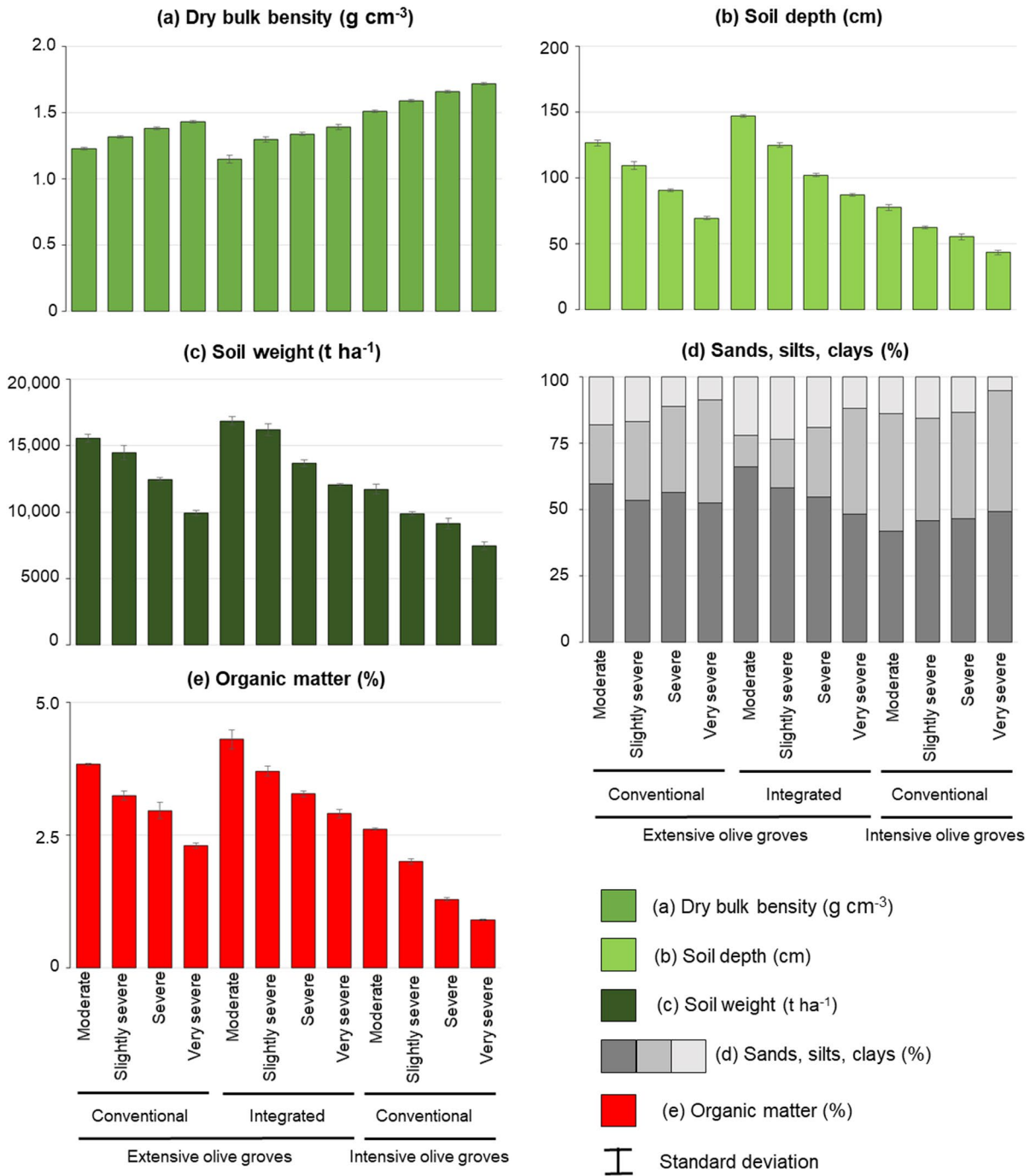
#### *Model calibration and validation strategy*

To apply the USLE model to all types of olive groves in Alentejo, main soil data for extensive-conventional, extensive-integrated and intensive-conventional groves were retrieved from Rodríguez Sousa et al. (2021) (Fig. 3). Based on these data (synthesized as the mean values of 4 groves in each group, and 3 samples per grove), key soil variables were extracted, resulting in statistical indicators across all four soil erosion levels (moderate to very severe). These were subsequently adapted to reflect the conditions of all remaining types of olive management models present in our case study area (Table 2). For extensive and organic olive groves, following the criteria of Gómez et al. (2009) and Romero-Gómez et al. (2017), it was assumed a higher fertility and lower compaction in soils (i.e. dry bulk density). The concentration

of clays was increased in line with decreases of sands and silts, due to a greater stability and quantity of colloidal aggregates than in integrated groves (Pleguezuelo et al. 2018). Following Rodríguez Sousa et al. (2019b), using published data on extensive organic olive grove as a proxy, it was assumed a higher depth in these groves, and thus we could estimate the weight of soil. The permanent plant cover for the intensive integrated and organic groves was modelled using the values of Rodríguez Sousa et al. (2021), which was higher than in the intensive conventional groves, with higher organic matter content and less soil compaction (Russo et al. 2016; Zuazo and Pleguezuelo 2009). According to Caraveli (2000) and Duarte et al. (2008), soil texture was maintained, with a predominance of loam textures due to the increase in clays together with the decreases in sands and silts, due to the influence of these types of agricultural management on the increase of soil stability. The research of Gómez et al. (2009) was used to calculate soil depth and weight in conventional and intensive groves with integrated and organic management.

To calibrate the highly-intensive olive grove projections, the calibrated data for intensive olive groves were used as a starting point. For highly intensive conventional groves, a greater dry bulk density was assumed (Gómez et al. 2009). It was also assumed a reduction in the clay soil content and soil depth, as well as a decrease in the organic matter content, following the trend and data in Rodríguez Sousa et al. (2022), which supports, from a pool of 80 plots, a lower soil fertility of highly intensive and conventional olive groves regarding to intensive and extensive, conventional groves. For integrated and highly intensive groves, starting from its equivalent counterpart in intensive groves and following the criteria by Rodríguez Sousa et al. (2019a), downgrades were made in the dry bulk density, organic matter, soil depth (conditioning soil weight) and clays. Finally, for organic and highly intensive olive groves, the same criteria described above were applied, with a baseline in organic and intensive olive groves.

The calibration of the USLE was obtained from Rodríguez Sousa et al. (2021, 2022) for extensive conventional, integrated and organic groves, as well as for highly-intensive and intensive conventional groves. Although the LS factor was calibrated for different slopes following MAPAMA (2017), the LS values were modified according to the slopes of the



**Fig. 3** Initial soil parameters in extensive (conventional and integrated), and intensive conventional olive groves: **a** bulk density (g cm<sup>-3</sup>); **b** soil depth (cm); **c** soil weight (t ha<sup>-1</sup>); **d**

soil texture (sands, silts and clays, in %); and **e** organic matter (%). Data extracted from Rodríguez Sousa et al. (2021)

**Table 2** Type of olive grove type to generate the modelled soil data, specifying the increases ( $\Delta$ ) and decreases ( $\nabla$ ) of each variable with respect to that reference grove

Type of olive grove		Reference olive grove	Soil parameters					
Tree density	Soil management		DBD (g cm <sup>-3</sup> )	Sands (%)	Silts (%)	Clays (%)	Sd (cm)	OM (%)
Highly-intensive (800–2000 trees ha <sup>-1</sup> )	Conventional	Intensive conventional	$\Delta$ 5%	$\Delta$ 2.5%	$\Delta$ 2.5%	$\nabla$ 5%	$\nabla$ 10%	$\nabla$ 5%
	Integrated	Intensive integrated	$\Delta$ 2.5%	$\Delta$ 1.25%	$\Delta$ 1.25%	$\nabla$ 2.5%	$\nabla$ 2.5%	$\nabla$ 2.5%
	Organic	Intensive organic	$\Delta$ 2.5%	$\Delta$ 1.25%	$\Delta$ 1.25%	$\nabla$ 2.5%	$\nabla$ 2.5%	$\nabla$ 2.5%
Intensive (200–800 trees ha <sup>-1</sup> )	Integrated	Intensive conventional	$\nabla$ 5%	$\nabla$ 5%	$\nabla$ 5%	$\Delta$ 10%	$\Delta$ 10%	$\Delta$ 10%
	Organic		$\nabla$ 10%	$\nabla$ 10%	$\nabla$ 10%	$\Delta$ 20%	$\Delta$ 20%	$\Delta$ 20%
Extensive (up to 200 trees ha <sup>-1</sup> )	Organic	Extensive integrated	$\nabla$ 5%	$\nabla$ 5%	$\nabla$ 5%	$\Delta$ 10%	$\Delta$ 5%	$\Delta$ 5%

DBS dry bulk density (g cm<sup>-3</sup>), Sd soil depth (cm), OM soil organic matter (%)

experimental groves, to make equivalent comparisons between the erosion rates estimated empirically and the erosion rates calculated through the USLE model. Based on these assumptions and data, for the rest of the crop typologies, soil losses were estimated by keeping R and P factor values constant at the regional level, calibrating the K factor through the corresponding soil data, and establishing the slopes of the LS factor according to the categories of moderate (10%), slightly severe (15%), severe (20%), and very severe (25%) potential for erosion. For the C factor, according to the same authors, a decrease of 64% was observed between conventional and integrated groves, along with a reduction rate of 37.5% between integrated and organic groves. By applying generic ratios amongst the diverse olive grove models, the C-factor values in the projections generated were estimated, resulting in greater C-factor values at higher planting densities and reduced with the implementation of soil cover crops characteristic of integrated and organic groves.

Finally, to foresee the impacts of erosion on the sustainability of olive groves in Alentejo, long-term simulations looking at 100- and 500-year periods, were conducted using STELLA software (STELLA 9.1.4 © STELLA 2010). This is a modelling software where, through a graphic interface based on Forrester diagrams, the progressive impacts of cumulative soil erosion over time can be estimated at multiple timescales, and for different crops. Due to the uncertainty that is necessarily linked to the trends in the expansion and spatial-temporal patterns of olive groves over time (Fraga et al. 2020), these projections

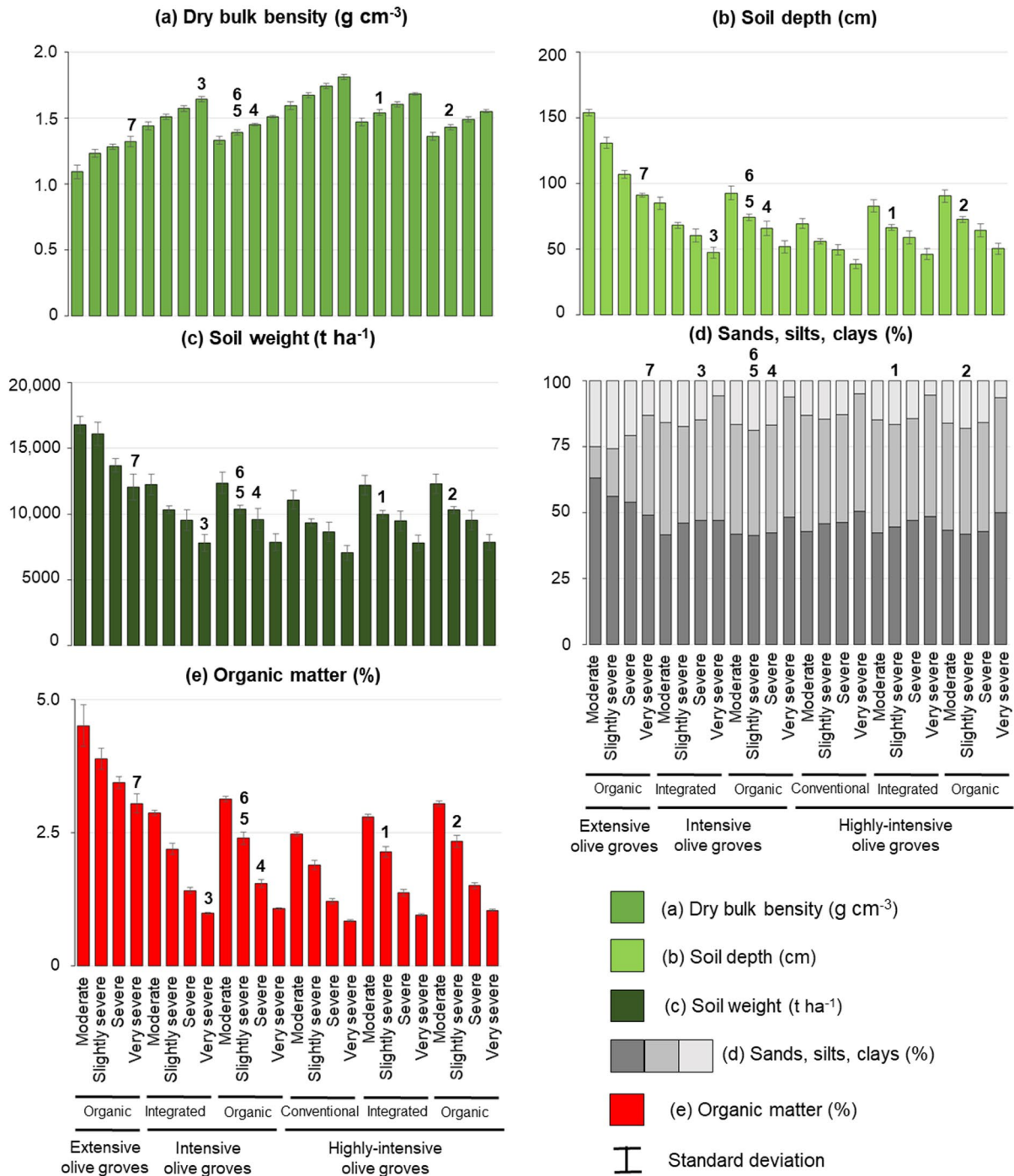
were calculated on the basis of a conservative scenario for olive grove management changes over time (business as usual). The simulations were made considering one assumption: the crop is assumed to be abandoned when the soil depth reaches 20 cm, which is the minimum useful depth for the cropland be considered profitable (Rodríguez Sousa et al. 2019b). In order to analyze the impact of rock fragments and soil thickness (Van Wesemael et al. 2000), we accounted for a differential mass transport of the different soil particles: the stones remaining in place and the soil fraction less than 2 mm being preferentially removed by erosion (Poesen and Lavee 1994; Ebabu et al. 2022). For the calibration of the USLE model, no differentiation was made, but for the modelling of the experimental groves, the simulations were carried out both with and without considering differential mass transport of the soil.

## Results

### Experimental and modelling results

Soil parameters calibrated for the different types of olive groves are summarized in Table 2, whilst those applied to model soil losses using USLE are summarized in Fig. 4. In this figure are attached data for each soil erosion level for the 6 olive groves according to their planting density and management (see specific results in Online Resource 1).

Intensive and highly-intensive groves showed a higher dry bulk density than extensive groves



**Fig. 4** Estimated soil parameters for each management model (highly-intensive conventional, integrated and organic, intensive integrated and organic, and extensive organic groves) and soil erosion level (moderate, slightly severe, severe and very severe). Data on: **a** soil dry bulk density (g cm<sup>-3</sup>); **b** soil

depth (cm); **c** soil weight per unit area (t ha<sup>-1</sup>); **d** percentages of sands, silts and clays for each projection, which determine soil texture, and **e** percentage of organic matter, are attached. Numbers indicate in which type of olive grove the experimental study crops are located for all parameters mentioned above

(minimum values between 1.1 and 1.3 g cm<sup>-3</sup> in organic management depending on the slopes of the plots). This parameter, in addition to increasing with erosion, increased for conventional management, reaching maximum values of 1.6–1.8 g cm<sup>-3</sup> in groves with maximum tree density. Conversely, soil depth was higher in organic extensive groves (up to 154.1 cm), with intermediate situations being evidenced in groves with high planting densities managed in an integrated or organic manner, the lowest depth being that of highly-intensive groves under conventional management (38.9 cm). A similar trend was evident for soil weight, with maximum values in extensive and organic groves on moderate slopes (16,794.7 t ha<sup>-1</sup>), and minimum values in highly-intensive and conventional groves (7044.5 t ha<sup>-1</sup>). There was a higher clay content in organic management. Finally, the maximum organic matter contents were up to 4.5% in the organic management of extensive groves, decreasing to 0.8% in highly-intensive groves managed conventionally with very severe slopes (up to 25%).

Table 3 shows the main soil characteristics of the experimental groves, which can condition soil loss rates.

All plots showed a similar texture, with a predominance of sands and a low content of fine soil particles (i.e. silts and clays). The lowest dry bulk density was observed in the extensive olive grove, showing less soil compaction. The most compacted soils were those with intensive olive groves managed organically, while highly-intensive olive groves (conventional and organic) showed an intermediate situation. Soil depths were also highly variable, although soils with a depth of less than 50 cm predominated, 2 plots with intensive and highly-intensive olive groves were the deepest, with values of 65 cm and 75 cm, respectively. The variability observed for these two variables resulted in very different soil weights among the groves, those with higher soil weights (total soil weight, soil weight < 2 mm, and soil weight for the 20 cm layer) being the plots with high planting densities managed organically. All the plots showed organic matter values between 2 and 4%, being an intermediate content, except for one plot of intensive organic olive grove, whose organic matter content was very high, exceeding 5%.

## USLE modelling of soil erosion rates

A constant rainfall erosivity value of 95 J ha<sup>-1</sup> (factor R) was assumed for all the groves. The slope ranges (Factor LS) were grouped into: (a) moderate (slopes up to 10%; b) slightly severe (10–15%); c) severe (15–20%); and d) very severe (up to 25%). For factor P we assumed a constant value of 1. The variability within factors K and C gave rise to different erosion estimates in the different olive groves. Figure 5 shows the calibration, in each type of crop, for K and C-factors (Fig. 5a; b), additionally showing the modelled soil erosions (Fig. 5c) (see specific results in Online Resource 2).

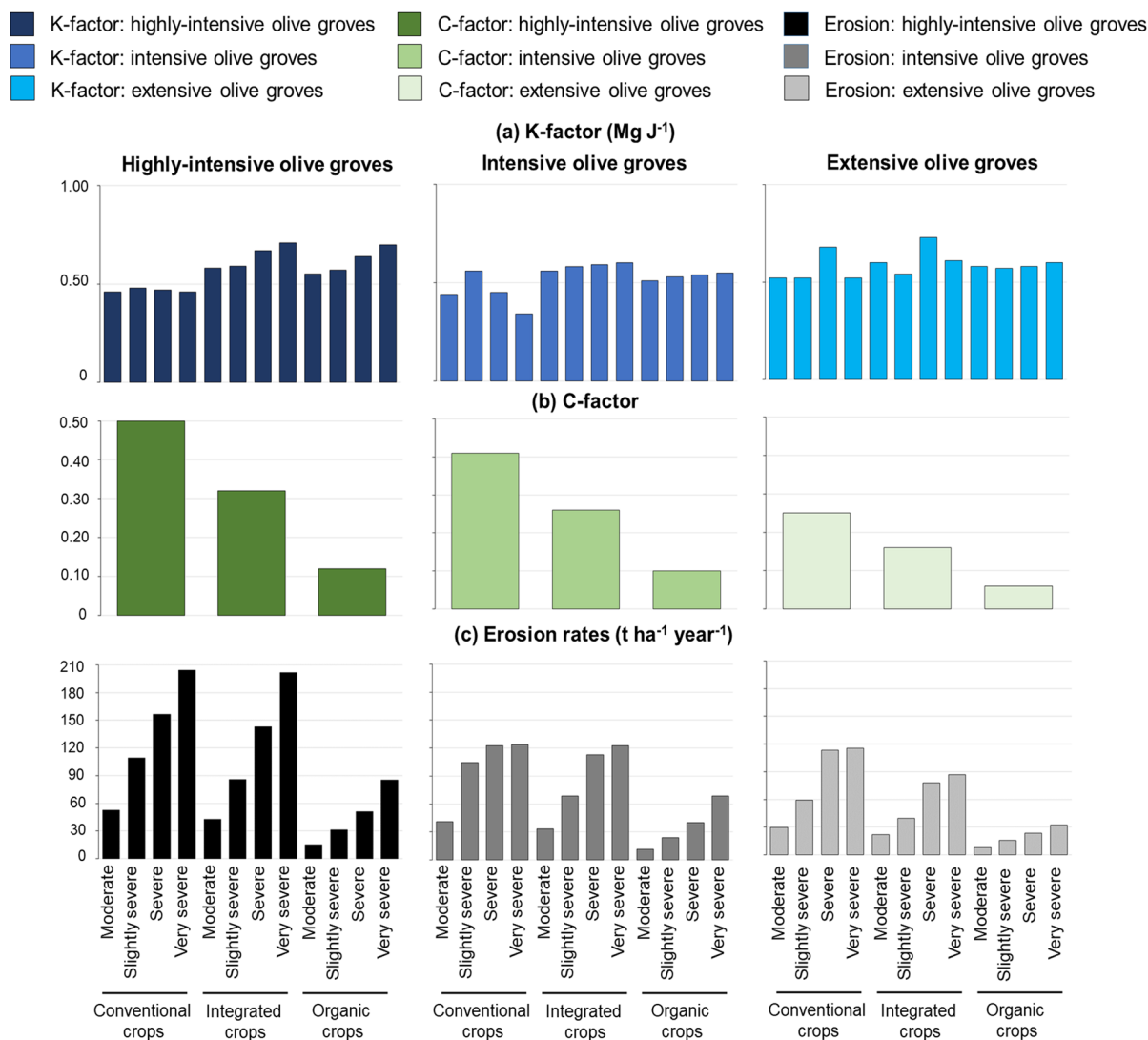
Given the constant nature of the R, LS and P factors, the differences in the potential erosion modelled of the groves are due to variations in the K and C factors. Soil erodibility was higher in highly intensive groves, and for higher erosive levels. Although the C factor previously modelled in other researches was 0.25, 0.16 and 0.06 in conventional, integrated and organic extensive groves, and 0.41 and 0.50 for intensive and highly-intensive conventional groves, the integrated and organic management of high-density groves showed decreases in this value due to a greater influence of soil cover. Thus, the C factor resulted in values of 0.26 and 0.10 in intensive integrated and organic groves, while for highly intensive groves, these values were 0.32 and 0.12, respectively.

A higher modelled soil loss was observed at higher plant densities. Within the extensive olive groves, those with the lowest potential erosion were the organically managed groves due to the usually permanent and total nature of the vegetation covers, with a maximum erosion of 32 t ha<sup>-1</sup> year<sup>-1</sup>, 72% and 63% lower than the conventional and integrated extensive olive groves, respectively. Intensive groves showed higher modelled erosion than extensive groves in conventional management (increases of 39–7% between the lower and higher slope territories), integrated (increases of 52–57%) and organic (increases of 47–113%), these increases being 77%, 93–133% and 90–167% when comparing highly intensive and extensive groves under equivalent management systems.

Through the erosion traps implemented in each study grove, the annual results of the quantified soil losses for the plots under study are synthesized in Table 4:

**Table 3** Main soil characteristics of the experimental olive groves (mean  $\pm$  standard deviation (SD)): dry bulk density (DBD, in  $\text{g cm}^{-3}$ ); percentages of stones, sands, silts and clays; corresponding soil texture (SCL: sandy-clay-loam; SL: sandy-loam); soil depth (Sd, in cm); soil weight (SW, in  $\text{t ha}^{-1}$ ); soil weight considering only particles lower than 2 mm (SW < 2 mm, in  $\text{t ha}^{-1}$ ); soil weight corresponding to the 20 cm (minimum useful depth, SW 20 cm, in  $\text{t ha}^{-1}$ ), and percentage of organic matter (OM)

Grove number	Type of olive grove	Soil characteristics											
		Tree density (trees $\text{ha}^{-1}$ )	Soil management	DBD ( $\text{g cm}^{-3}$ )	Stones (%)	Sands (%)	Silts (%)	Clays (%)	Soil texture	Sd (cm)	SW ( $\text{t ha}^{-1}$ )	SW < 2 mm ( $\text{t ha}^{-1}$ )	SW 20 cm ( $\text{t ha}^{-1}$ )
1	Highly-intensive	Inte-grated	1.4 $\pm$ 0.1	27.8 $\pm$ 0.9	57.9 $\pm$ 2.2	20.2 $\pm$ 1.3	21.9 $\pm$ 1.4	SCL	40	5726.2 $\pm$ 123.4	4134.3 $\pm$ 89.1	2800.0 $\pm$ 280.0	2.2 $\pm$ 0.5
2	Highly-intensive	Organic (Biodynamic)	1.3 $\pm$ 0.1	44.4 $\pm$ 2.2	68.7 $\pm$ 1.1	12.1 $\pm$ 2.4	19.3 $\pm$ 1.1	SL	65	8817.5 $\pm$ 62.9	4902.5 $\pm$ 34.9	2600.0 $\pm$ 260.0	2.2 $\pm$ 0.3
3	Intensive	Inte-grated	1.3 $\pm$ 0.1	21.1 $\pm$ 5.3	66.9 $\pm$ 2.2	11.9 $\pm$ 1.2	21.1 $\pm$ 1.1	SCL	25	3310.9 $\pm$ 114.7	2612.3 $\pm$ 90.5	2600.0 $\pm$ 260.0	2.3 $\pm$ 0.2
4	Intensive	Organic	1.5 $\pm$ 0.1	47.1 $\pm$ 1.3	54.2 $\pm$ 1.8	21.8 $\pm$ 2.8	23.9 $\pm$ 1.1	SCL	20	3068.2 $\pm$ 125.7	1623.1 $\pm$ 67.5	3000.0 $\pm$ 300.0	3.7 $\pm$ 0.3
5	Intensive	Organic	1.6 $\pm$ 0.1	25.9 $\pm$ 1.7	67.7 $\pm$ 1.1	11.2 $\pm$ 0.2	21.1 $\pm$ 1.1	SCL	75	12,387.9 $\pm$ 312.5	9179.4 $\pm$ 231.5	3200.0 $\pm$ 320.0	5.2 $\pm$ 1.2
6	Intensive	Organic	1.5 $\pm$ 0.1	57.1 $\pm$ 2.3	68.9 $\pm$ 1.3	9.2 $\pm$ 2.2	21.9 $\pm$ 1.4	SCL	50	7657.5 $\pm$ 224.2	3285.1 $\pm$ 96.2	3000.0 $\pm$ 300.0	3.1 $\pm$ 0.8
7	Extensive	Organic	1.3 $\pm$ 0.1	28.8 $\pm$ 5.6	63.4 $\pm$ 4.6	13.4 $\pm$ 3.4	23.2 $\pm$ 1.3	SCL	25	3156.1 $\pm$ 277.6	2247.1 $\pm$ 197.7	2600.0 $\pm$ 260.0	2.2 $\pm$ 0.9



**Fig. 5** Theoretical estimates of factor K (a, soil erodibility,  $\text{Mg J}^{-1}$ ), factor C (b, soil cover; one single value per type of olive grove, regardless of the slope of the land), and erosion (c,  $\text{t ha}^{-1} \text{ year}^{-1}$ ) for extensive, intensive and highly intensive

olive groves managed conventionally, integrated or organically according to the different levels of slope stipulated: moderate (up to 10%), slightly severe (up to 15%), severe (up to 20%), and very severe (up to 25%)

The highest field erosion rate, higher than  $20 \text{ t ha}^{-1} \text{ year}^{-1}$  was observed for an intensive olive grove with integrated management (grove 3). Field erosion higher than  $10 \text{ t ha}^{-1} \text{ year}^{-1}$  was evidenced in a highly intensive integrated olive grove (grove 1). For the rest of the groves, although the extensive olive grove showed the lowest erosion rate (i.e.  $0.003 \text{ t ha}^{-1} \text{ year}^{-1}$ ), the annual rates were lower than  $1 \text{ t ha}^{-1} \text{ year}^{-1}$ .

Field and modelled data showed large differences amongst them. The field soil erosion calculated for the highly intensive integrated and organic olive groves were, respectively 90% and 97% lower than the modelled erosion, corresponding to plots with slopes between 10–15% ( $108$  and  $31 \text{ t ha}^{-1} \text{ year}^{-1}$ ). Intensive organic groves, with slopes ranged around 15%, showed a lower erosion of 99% compared to the USLE outputs ( $24 \text{ t ha}^{-1} \text{ year}^{-1}$ ). The intensive

**Table 4** Mean soil erosion rates ( $t\ ha^{-1}\ year^{-1}$ ) measured using sediment fence plots and estimated using the USLE model for each experimental olive groves of this study

Grove number	Type of olive grove		Erosion rates ( $t\ ha^{-1}\ year^{-1}$ )	USLE erosion rates ( $t\ ha^{-1}\ year^{-1}$ )
	Tree density (trees $ha^{-1}$ )	Soil management		
1	Highly-intensive (1925)	Integrated	10.89	108.9
2	Highly-intensive (1186)	Organic (Biodynamic)	0.41	31.1
3	Intensive (272)	Integrated	22.76	138.6
4	Intensive (284)	Organic	0.11	35.9
5	Intensive (341)	Organic	0.05	24.1
6	Intensive (339)	Organic	0.14	24.1
7	Extensive (104)	Organic	0.003	32.0

integrated olive grove (23% slope) also showed an erosion rate lower by 81% with respect to the modelled value ( $138\ t\ ha^{-1}\ year^{-1}$ ). Finally, the extensive organic olive grove, with a slope greater than 20%, showed 99% less erosion rates with respect to the modelled value ( $32\ t\ ha^{-1}\ year^{-1}$ ).

Long-term impacts of erosion on the sustainability of olive groves

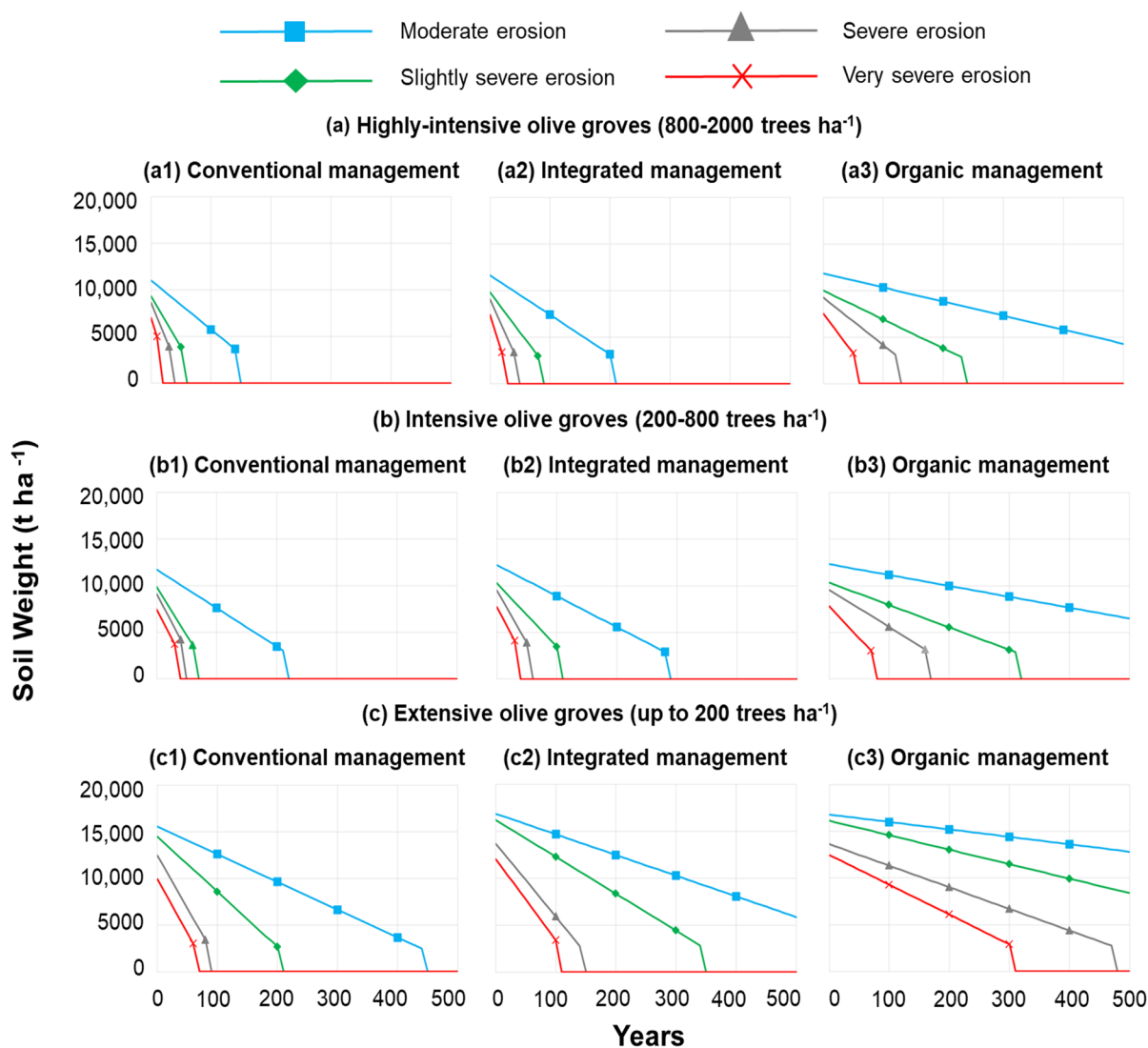
For the 36 types of olive grove obtained combining tree density, far, management and erosion levels the 100-year and 500-year simulations were carried out to evaluate their future sustainability. Table 5 the lifespan at which each olive grove cease to be sustainable, extracted from the 100-year projections.

Highly-intensive and intensive olive groves conventionally managed in slopes greater than 10% showed a future sustainability of less than 80 years, highlighting the low sustainability levels of this type of olive grove in land with high erosion (i.e. 20 years). A similar trend was observed for high-density olive groves under integrated management, while organic olive groves, regardless of their planting density, were not sustainable in the 100-year projection (slopes of 20–25%). Figure 6 shows the trend of each management model over the 500 years simulated.

The 36 types showed an unsustainable soil loss at 500 years, especially those groves with slightly severe-very severe erosion rates. Extensive organic groves had a greater long-term sustainability, with rates higher than 500 years. Although organic groves increased farm sustainability rates across all densities

**Table 5** Lifespan span (years) after which each grove ceases to be sustainable (LS) or non-sustainable, specifying the olive grove classification according to planting density (highly-intensive, intensive and extensive groves), soil management (conventional, integrated and organic), as well as their degree of erosion, conditioned by the slope (percent range)

Type of olive grove	Slope (%)	Erosion level	LS (years)
Highly-intensive conventional	10–15	Slightly severe	80
	15–20	Severe	50
	20–25	Very severe	20
Highly-intensive integrated	10–15	Slightly severe	90
	15–20	Severe	50
	20–25	Very severe	30
Highly-intensive organic	20–25	Very severe	60
	Intensive conventional	10–15	Slightly severe
15–20		Severe	40
20–25		Very severe	30
Intensive integrated	15–20	Severe	50
	20–25	Very severe	30
Intensive organic	20–25	Very severe	80
Extensive conventional	15–20	Severe	80
	20–25	Very severe	60



**Fig. 6** Projections at 500-year for the soil weight estimated for the 36 olive grove management types considered by combining tree density (highly-intensive, intensive and extensive), man-

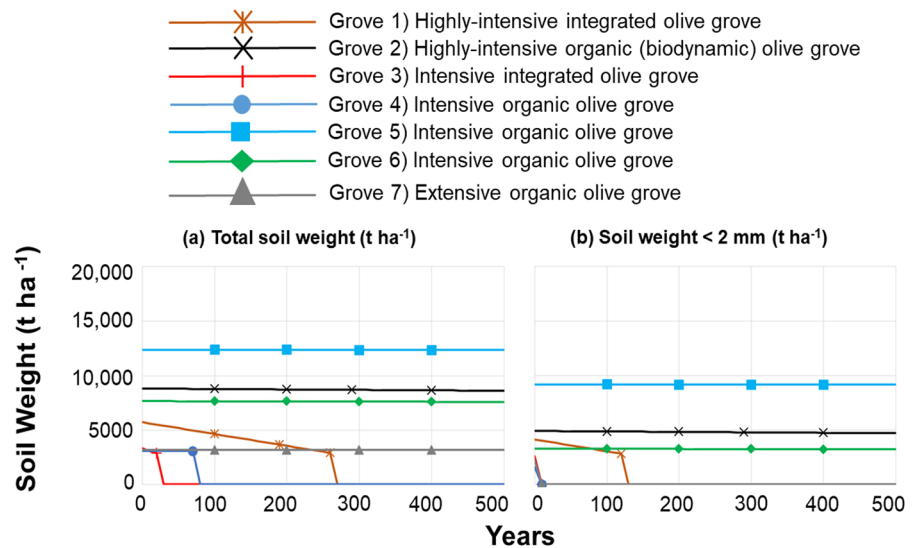
agement models (conventional, integrated and organic) and erosion levels depending on slopes (moderate, slightly severe, severe, and very severe)

(Fig. 6), the increase in this factor showed an inverse relationship with crop sustainability. Thus, highly-intensive and intensive groves showed low sustainability under very severe erosion levels (29 and 45 years in conventional, 70 and 86 years in integrated and 238 and 256 years in organic management regarding extensive groves).

The empirical soil erosion levels for the 7 experimental olive groves showed a much higher sustainability and lifespan than the modelled projections (Fig. 7). Considering total soil weight (Fig. 7a), the

100-year simulations showed a higher sustainability, losing only 2 plots of intensive olive groves with integrated and organic management (groves 3 and 4, with lifespans of circa 30 and 80 years, respectively). However, when stones are not considered as erodible material (Fig. 7b), the extensive organic grove (grove 7) would also be lost, due to its soil weight being lower than the threshold assumed for agriculture abandonment (i.e. soil depth lower than 20 cm). The highly-intensive integrated olive groves also reduced their lifespan at 270 years.

**Fig. 7** Projections at 500-year for the experimental study plots: **a** considering total soil weight; **b** only considering the weight of the soil particles lower than 2 mm



## Discussion

### Differences in field vs. modelled soil erosion in the seven experimental olive groves

Our field results show that intensive olive groves with herbicides and vegetation stripe cover densities lower than 20%, showed higher erosion rates. This finding reflects how chemical inputs inhibit the development of soil fauna and flora, generating weaker soils where the dragging of surface materials is maximized (Metzidakis et al. 2008; Baniyas et al. 2017). Highly-intensive and organic groves, where the vegetation cover was higher than 50% showed a minimal impact of erosive processes, as well as the extensive grove, with a 100% of vegetation cover. These findings show how organic or biodynamic models guarantee greater sustainability of these groves with respect to intensive and highly-intensive groves managed in an integrated or conventional ways (Romero-Gómez et al. 2017; Mairech et al. 2020; Santoni et al. 2022). It is important to highlight the role of stones as erosion mitigating agents, being non-erodible material (Rodríguez Sousa et al. 2019b). When analyzing the experimental olive groves assuming only soil particles smaller than 2 mm as erodible fraction, a decrease in long-term sustainability was observed in groves whose total soil weight was less than 6000 t ha<sup>-1</sup> and where the percentage of stones was higher than 28%.

Soil erosion has negative impacts on soil fertility, decreasing production yields, potentially leading to

land abandonment (van Leeuwen et al. 2019). There are multiple tools available to estimate soil loss. The most widespread method to estimate soil losses is through the Universal Soil Loss Equation (USLE), a model that calculates surface erosion for each grove and region (Wischmeier and Smith 1960; Fistikoglu and Harmancioglu 2002). Despite the widespread applicability of this equation, its limitations, mainly derived from the need to undertake generic agronomic assumptions in response to the complexity of calibrating structural soil parameters that vary at the plot scale, have led to the delivery of models that are more tightly adapted to contingent local conditions, such as the RUSLE (revised USLE) or MUSLE (modified USLE) (Benavidez et al. 2018; Sadeghi et al. 2014) models. All these models still require to make adjustments to specific local conditions using field measurements.

In this research, the USLE model was calibrated for each olive grove type, resulting in an overestimation of the soil loss values, as compared to the erosion quantified empirically through the use of sediment fences, a pioneering test in the context of Iberian olive groves. Some limitations are inherent to the quantification of erosion through sediment fences, where it is possible that the mesh size allows the filtration of between 10 and 30% of fine soil particles (Wilson et al. 2021). Other limitation is the fact that our field results were monitored during a slightly dry year (less than 500 mm in 2022; whilst the long-term rainfall average is between 550 and 600 mm), which

resulted in lower soil loss rates than in a typical year. The application of the USLE model produced much larger values, and were less reflective of the conditions in each olive orchard than the empirical values.

In this sense, planting density is a factor that strongly influences the calibration of the cover factor C, increasing it in highly-intensive and intensive groves, where trees are still younger and thus smaller than in extensive groves (Gabriels et al. 2003; AEMO 2020). Such an increase, together with the assumption that no conservation practices or terraced crops (i.e. P factor) are implemented on any agricultural plot, lead to an increase in the erosion estimate for highly-intensive and intensive groves (Rodríguez Sousa et al. 2019a). In addition to the consideration of planting density in land erosion, it is key, according to our field results, to consider soil management as a key driver of erosion mitigation (Kairis et al. 2013; Gómez et al. 2018). In Alentejo, the implementation of plant cover is a typical agronomic characteristic of, specifically, integrated and organic management models, even in high density groves (Fleskens et al. 2009; Gómez et al. 2009; Santoni et al. 2022). Our results are aligned with those of other researchers, in which cover is an essential measure that provides a protective cover to the soil, increase water infiltration, promotes soil organic matter (experimental values up to 5.2%) and favors the formation of soil aggregates that act as soil retention particles in the face of soil loss, (Durán Zuazo et al. 2006; Zuazo and Pleguezuelo 2009).

#### Impacts of intensification on olive sustainability in Alentejo

Agricultural intensification is a process aimed at maximizing crop production (Caraveli 2000). However, this trend is associated with negative ecological connotations such as an increased risk of diffuse pollution and erosion (de Graaff et al. 2010; Gómez-Limón et al. 2012; Gómez et al. 2014). Erosion has repercussions on sustainability, negatively affecting land fertility and influencing the development of any grove (Uri 2000; de Vente et al. 2013). Although this statement has been widely discussed (Gómez et al. 2014; Rodríguez Sousa et al. 2019a), it should be noted that there are some factors hinting that intensification did not affect sustainability (Metzidakis et al. 2008). The negative connotations associated with agricultural

intensification derive from the implementation of specific management practices such as the unregulated application of chemical fertilizers, the use of machinery and tillage practices, and the elimination of any type of plant cover in order to avoid water and nutrient competition with the olive tree (Mairech et al. 2020). Such agronomic practices enhance soil erosion and thus reduce their sustainability (Duarte et al. 2008; Rodríguez Sousa et al. 2020). However, olive groves with high planting densities can be also managed organically, which can improve its sustainability (Metzidakis et al. 2008; Guerrero-Casado et al. 2021).

Despite the relatively short sampling period, the results obtained allow us to identify differences in the estimates of erosion resulting from theoretical models (USLE) on the one hand, and field work at the plot scale on the other, with a focus on specific crops (olive groves) and a geographic context (SW Iberia). To increase the robustness of the results, longer term monitoring schemes must be applied, in line with previous research by Shakesby (2011), or Prats et al. (2012; 2016), as well as expanding the experiment to other areas of the Iberian Peninsula, and the wider Mediterranean macro-region, where other distinct olive grove management models can be found. According to our results, soil management is the key determining factor of farm sustainability, with the increase in tree density being largely a parameter of agronomic characterization (Kairis et al. 2013; AEMO 2020; Camposeo et al. 2022). The difference between these two factors is responsible for the lower sustainability evidenced by the models, where the importance of planting density is increased, overestimating the loss of soil per unit of area, implying earlier abandonment than estimated based on field data (Figs. 6 and 7). In contrast, there are soil management practices that, according to our results, inarguably promote sustainability, including application of integrated and organic agricultural practices such as minimizing herbicides and allowing the growth of plant cover, which prevent soil degradation (Zuazo and Pleguezuelo 2009; Carmona-Torres et al. 2014).

#### Conclusions

Our main conclusions are the following: (a) our study shows an overestimation of the soil erosion model results as compared to the field empirical soil erosion

values. These differences are mainly due to the general assumptions that are required to maximize the applicability of the models, which can lead to significant differences with reality; (b) specifically, model assumptions such as the removal of vegetation in groves with high densities (i.e. C-factor) are at the root of the high erosion rates estimated through the USLE model; (c) results from long-term projections clearly indicate that planting density is a secondary factor that does not directly affect olive grove sustainability, and that soil management models should be considered as the key factor. The sustainability of organically managed groves, which are defined by higher soil fertility and lower soil erosion, is similar across highly-intensive, intensive and extensive olive groves.

Future lines of research should focus to enlarge the empirical data series, extending the spatial and temporal scale of the present research, in order to standardize the classification of impacts of each soil management and agriculture intensification on soil erosion and consequently, agricultural productivity. Further research should also focus at enhancing the functionality, productivity and sustainability of soils under conventional and integrated management.

**Acknowledgements** To the SUSTAINOLIVE project (<https://sustainolive.eu/?lang=en>; PRIMA EU Programme), as a source of funding for José Muñoz-Rojas. To the FCT (Fundação para a Ciência e a Tecnologia – Portugal), the CHANGE laboratory and MED - Mediterranean Institute for Agriculture, Environment and Development (University of Évora), funded by Project UIDB/05183/2020. Sergio Prats and Clarisse Brígido were supported by contracts funded by the FCT (CEECIND/01473/2020 and CEECIND/00093/2018, respectively). Antonio Alberto Rodríguez Sousa, current Assistant Professor, was a postdoctoral researcher at the UCM assigned to the MED and University of Évora (Portugal) during the development of this research. This author is acknowledged for the support of all the aforementioned institutions, and was specifically supported by a Margarita Salas Postdoctoral Contract for the Training of Young PhDs (Multiannual call for the requalification of the Spanish University System for 2021–2023; <https://www.ucm.es/ct31-21>) funded by UCM through the Ministry of Universities, Government of Spain and the European Union – NextGenerationEU, being the main researcher of the ASMO - Análisis comparativo de la Sostenibilidad y Multifuncionalidad Oliverera en dos regiones de la Península Ibérica a través de un enfoque de ecología del paisaje: el Alentejo (Portugal) y el Sureste de Madrid (España) project, within which this research fits. Finally, to the social actors and farmers who gave their authorization to carry out the corresponding studies in the experimental olive groves of the present research, and to María Aurora Rodríguez Sousa, for

their support and contributions to the completion of the first drafts of this manuscript.

**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by AARS, JM-R, CB and SAP. The main manuscript text was written by AARS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. The implementation of this research was additionally funded by a Margarita Salas postdoctoral contract for the training of young PhDs (multiannual call for the requalification of the Spanish University System for 2021–2023; <https://www.ucm.es/ct31-21>), by University Complutense of Madrid through the Ministry of Universities, Government of Spain and the European Union – NextGenerationEU. The implementation of this study has been secondarily funded by the FCT (Fundação para a Ciência e a Tecnologia – Portugal), the CHANGE laboratory and MED—Mediterranean Institute for Agriculture, Environment and Development (University of Évora), funded by Project UIDB/05183/2020. This study has been supported by the SUSTAINOLIVE project (<https://sustainolive.eu/?lang=en>; PRIMA EU Programme).

#### Declarations

**Competing interests** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

#### References

AEMO (Asociación Española de Municipios del Olivo/Spanish Association of Municipalities of Olive groves) (2020) Aproximación a los costes del cultivo del olivo. Desarrollo y conclusiones del estudio AEMO. Córdoba, Spain. <https://www.aemo.es/blog/noticias-aemo-1/post/aemo-actualiza-a-2020-su-estudio-de-costes-del-cultivo-del-olivo-183>. Accessed 1 Oct 2022

- Aranda V, Ayora-Cañada MJ, Domínguez-Vidal A, Martín-García JM, Calero J, Delgado R, Verdejo T, González-Vila FJ (2011) Effect of soil type and management (organic vs. conventional) on soil organic matter quality in olive groves in a semi-arid environment in Sierra Mágina Natural Park (S Spain). *Geoderma* 164(1–2):54–63
- Auerswald K, Fiener P, Martin W, Elhaus D (2014) Use and misuse of the K factor equation in soil erosion modeling: an alternative equation for determining USLE nomograph soil erodibility values. *CATENA* 118:220–225
- Banias G, Achillas C, Vlachokostas C, Moussiopoulos N, Stefanou M (2017) Environmental impacts in the life cycle of olive oil: a literature review. *J Sci Food Agric* 97(6):1686–1697
- Benavidez R, Jackson B, Maxwell D, Norton K (2018) A review of the (Revised) Universal Soil Loss Equation ((R) USLE): with a view to increasing its global applicability and improving soil loss estimates. *Hydrol Earth Syst Sci* 22(11):6059–6086
- Bouyoucos GJ (1962) Hydrometer method improved for making particle size analyses of soils 1. *Agron J* 54(5):464–465
- Camposo S, Vivaldi GA, Russo G, Melucci FM (2022) Intensification in olive growing reduces global warming potential under both integrated and organic farming. *Sustainability* 14(11):6389
- Caraveli H (2000) A comparative analysis on intensification and extensification in Mediterranean agriculture: dilemmas for LFAs policy. *J Rural Stud* 16(2):231–242
- Carmona-Torres C, Parra-López C, Hinojosa-Rodríguez A, Sayadi S (2014) Farm-level multifunctionality associated with farming techniques in olive growing: an integrated modeling approach. *Agric Syst* 127:97–114
- Copernicus Land Monitoring Service (2018) CLC (CORINE Land Cover) Copenhagen, Denmark. <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018>. Accessed 30 March 2023
- D'Auria A, Marano-Marcolini C, Čehić A, Tregua M (2020) Oleotourism: a comparison of three mediterranean countries. *Sustainability* 12(21):8995
- De Gennaro B, Notarnicola B, Roselli L, Tassielli G (2012) Innovative olive-growing models: an environmental and economic assessment. *J Clean Prod* 28:70–80
- de Graaff J, Duarte F, Fleskens L, de Figueiredo T (2010) The future of olive groves on sloping land and ex-ante assessment of cross compliance for erosion control. *Land Use Policy* 27(1):33–41
- de Vente J, Poesen J, Verstraeten G, Govers G, Vanmaercke M, Van Rompaey A, Arabkhedri M, Boix-Fayos C (2013) Predicting soil erosion and sediment yield at regional scales: where do we stand? *Earth-Sci Rev* 127:16–29
- DGT (Direção-Geral do Território) (2022) Cartografia temática. Lisbon, Portugal. <https://www.dgterritorio.gov.pt/cartografia/cartografia-topografica/ortofotos>. Accessed 5 Dec 2022
- Duarte F, Jones N, Fleskens L (2008) Traditional olive orchards on sloping land: sustainability or abandonment? *J Environ Manag* 89(2):86–98
- Durán Zuazo VH, Martínez JR, Pleguezuelo CR, Martínez Raya A, Rodríguez BC (2006) Soil-erosion and runoff prevention by plant covers in a mountainous area (SE Spain): implications for sustainable agriculture. *Environmentalist* 26(4):309–319
- Ebabu K, Tsunekawa A, Haregeweyn N, Tsubo M, Adgo E, Fenta AA, Meshesha DT, Berihun ML, Sultan D, Vanmaercke M, Panagos P, Borrelli P, Langendoen EJ, Poesen J (2022) Global analysis of cover management and support practice factors that control soil erosion and conservation. *Int Soil Water Conserv Res* 10(2):161–176
- EC (European Commission) (2020) Eurobarometer: Europeans, Agriculture and the CAP. Brussels, Belgium. <https://europa.eu/eurobarometer/surveys/detail/2229>. Accessed 15 Oct 2022
- EUROSTAT (European Statistics) (2021) Agriculture, forestry and fishery statistics. Luxembourg. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agriculture,\\_forestry\\_and\\_fishery\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agriculture,_forestry_and_fishery_statistics). Accessed 07 Oct 2022
- Fistikoglu O, Harmancioglu NB (2002) Integration of GIS with USLE in assessment of soil erosion. *Water Resour Manag* 16(6):447–467
- Fleskens L, Duarte F, Eicher I (2009) A conceptual framework for the assessment of multiple functions of agroecosystems: a case study of Trás-os-Montes olive groves. *J Rural Stud* 25(1):141–155
- Fraga H, Pinto JG, Santos JA (2020) Olive tree irrigation as a climate change adaptation measure in Alentejo, Portugal. *Agric Water Manag* 237:106193
- Fregapan G, Salvador MD (2019) Chemical and sensory characteristics of extra virgin olive oils produced in central Iberian Peninsula under the protected designation of origin quality scheme. *Eur J Lipid Sci* 121(3):1800134
- Gabriels D, Ghekiere G, Schiettecatte W, Rottiers I (2003) Assessment of USLE cover-management C-factors for 40 crop rotation systems on arable farms in the Kemmelbeek watershed, Belgium. *Soil till Res* 74(1):47–53
- Gisbert Blanquer JM, Ibáñez Asensio S, Moreno Ramón H (2012) El factor K de la ecuación universal de pérdidas de suelo (USLE). <https://riunet.upv.es/handle/10251/16850>. Accessed 5 Dec 2022
- Gómez JA, Sobrinho TA, Giráldez JV, Fereres E (2009) Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. *Soil till Res* 102(1):5–13
- Gómez JA, Infante-Amate J, González de Molina M, Vanwalleghem T, Taguas EV, 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(2):170–198
- Gómez JA, Campos M, Guzmán G, Castillo-Llanque F, Vanwalleghem T, Lora Á, Giráldez JV (2018) Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. *Environ Sci Pollut Res* 25(2):977–989
- Gómez-Limón JA, Picazo-Tadeo AJ, Reig-Martínez E (2012) Eco-efficiency assessment of olive farms in Andalusia. *Land Use Policy* 29(2):395–406
- Guerrero-Casado J, Carpio AJ, Tortosa FS, Villanueva AJ (2021) Environmental challenges of intensive woody crops: the case of super high-density olive groves. *Sci Total Environ* 798:149212

- INE (Instituto Nacional de Estadística/National Statistical Institute) (2022a) Agricultural Statistics - 2021. Lisbon, Portugal. [https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine\\_destaques&DESTAQUESdest\\_boui=539491784&DESTAQUESmodo=2](https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_destaques&DESTAQUESdest_boui=539491784&DESTAQUESmodo=2). Accessed 21 Oct 2022a
- INE (Instituto Nacional de Estadística/National Statistical Institute) (2022b) Base de Dados. Statistics Portugal – 2022. Lisbon, Portugal. [https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine\\_indicadores&userLoadSave=Load&userTableOrder=9286&tipoSelecao=1&contexto=pq&selTab=tab1&submitLoad=true&xlang=pt](https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&userLoadSave=Load&userTableOrder=9286&tipoSelecao=1&contexto=pq&selTab=tab1&submitLoad=true&xlang=pt). Accessed 18 April 2023
- Kairis O, Karavitis C, Kounalaki A, Salvati L, Kosmas C (2013) The effect of land management practices on soil erosion and land desertification in an olive grove. *Soil Use Manag* 29(4):597–606
- Kinnell PIA (2010) Event soil loss, runoff and the Universal Soil Loss Equation family of models: a review. *J Hydrol* 385(1–4):384–397
- Lima-Cueto FJ, Blanco-Sepúlveda R, Gómez-Moreno ML (2018) Soil erosion and environmental regulations in the european agrarian policy for olive groves (*Olea europaea*) of southern Spain. *Agrociencia* 52(3):293–308
- Mairech H, Lopez-Bernal A, Moriondo M, Dibari C, Regni L, Proietti P, Villalobos FJ, Testi L (2020) Is new olive farming sustainable? A spatial comparison of productive and environmental performances between traditional and new olive orchards with the model OliveCan. *Agric Syst* 181:102816
- Maldonado AD, Ramos-López D, Aguilera PA (2019) The role of cultural landscapes in the delivery of provisioning ecosystem services in protected areas. *Sustainability* 11(9):2471
- MAPAMA (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente/Ministry of Agriculture and Fisheries, Food and Environment) (2017) Aceite de olive y aceituna de mesa. Spain. <http://www.mapama.gob.es/es/agricultura/temas/producciones-agricolas/aceite-oliva-y-aceitunamesa/>. Accessed 8 Jan 2023
- Metzidakis I, Martinez-Vilela A, Nieto GC, Basso B (2008) Intensive olive orchards on sloping land: good water and pest management are essential. *J Environ Manag* 89(2):120–128
- Pastor M, García-Vila M, Soriano MA, Vega V, Fereres V (2007) Productivity of olive orchards in response to tree density. *J Horticult Sci Biotechnol* 82(4):555–562
- Pérez JR, Loureiro S, Menezes S, Palma P, Fernandes RM, Barbosa IR, Soares AM (2010) Assessment of water quality in the Alqueva Reservoir (Portugal) using bioassays. *Environ Sci Pollut Res* 17(3):688–702
- Pizzolotto R, Mazzei A, Bonacci T, Scalercio S, Iannotta N, Brandmayr P (2018) Ground beetles in Mediterranean olive agroecosystems: their significance and functional role as bioindicators (Coleoptera, Carabidae). *PLoS ONE* 13(3):e0194551
- Pleguezuelo CRR, Zuazo VHD, Martínez JRF, Peinado FJM, Martín FM, Tejero IFG (2018) Organic olive farming in Andalusia, Spain. A review. *Agron Sustain Dev* 38(2):1–16
- Poesen J, Lavee H (1994) Rock fragments in top soils: significance and processes. *CATENA* 23(1–2):1–28
- Prats SA, MacDonald LH, Monteiro M, Ferreira AJ, Coelho CO, Keizer JJ (2012) Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. *Geoderma* 191:115–124
- Prats SA, Malvar MC, Vieira DCS, MacDonald L, Keizer JJ (2016) Effectiveness of hydromulching to reduce runoff and erosion in a recently burnt pine plantation in central Portugal. *Land Degrad Dev* 27(5):1319–1333
- Renard KG, Meyer LD, Foster GR (1997) Introduction and history. Predicting soil erosion by water: a guide to conservation, planning with the revised universal soil loss equation (RUSLE). U.S. Department of Agriculture, Agriculture Handbook N° 703
- Rey PJ, Manzaneda AJ, Valera F, Alcantara JM, Tarifa R, Isla J, Molina-Pardo JL, Calvo G, Salido T, Gutiérrez JE, Ruiz C (2019) Landscape-moderated biodiversity effects of ground herb cover in olive groves: implications for regional biodiversity conservation. *Agric Ecosyst Environ* 277:61–73
- Rodríguez Sousa AA, Barandica JM, Rescia AJ (2019a) Application of a dynamic model using agronomic and economic data to evaluate the sustainability of the olive grove landscape of Estepa (Andalusia, Spain). *Landsc Ecol* 34(7):1547–1563
- Rodríguez Sousa AA, Barandica JM, Rescia AJ (2019b) Estimation of soil loss tolerance in olive groves as an indicator of sustainability: the case of the Estepa Region (Andalusia, Spain). *Agronomy* 9(12):785
- Rodríguez Sousa AA, Barandica JM, Aguilera PA, Rescia AJ (2020) Examining potential environmental consequences of climate change and other driving forces on the sustainability of Spanish olive groves under a socio-ecological approach. *Agriculture* 10(11):509
- Rodríguez Sousa AA, Muñoz-Rojas J, Pinto-Correia T, Aguilera PA, Barandica JM, Rescia AJ (2021) A Comparative analysis of soil loss tolerance and productivity of the Olive Groves in the Protected Designation of Origin (PDO) Areas Norte Alentejano (Portugal) and Estepa (Andalusia, Spain). *Agronomy* 11(4):665
- Rodríguez Sousa AA, Tribaldos-Anda C, Prats SA, Brígido C, Muñoz-Rojas J, Rescia AJ (2022) Impacts of fertilization on environmental quality across a gradient of Olive Grove Management Systems in Alentejo (Portugal). *Land* 11(12):2194
- Rodríguez-Cohard JC, Sánchez-Martínez JD, Gallego-Simón VJ (2019) Olive crops and rural development: capital, knowledge and tradition. *Reg Sci Policy Pract* 11(6):935–949
- Rodríguez-Entrena M, Barreiro-Hurlé J, Gómez-Limón JA, Espinosa-Goded M, Castro-Rodríguez J (2012) Evaluating the demand for carbon sequestration in olive grove soils as a strategy toward mitigating climate change. *J Environ Manag* 112:368–376
- Romero-Gómez M, Castro-Rodríguez J, Suárez-Rey EM (2017) Optimization of olive growing practices in Spain from a life cycle assessment perspective. *J Clean Prod* 149:25–37
- Russo C, Cappelletti GM, Nicoletti GM, Di Noia AE, Michalopoulos G (2016) Comparison of European olive production systems. *Sustainability* 8(8):825

- Sadeghi SHR, Gholami L, Khaledi Darvishan A, Saeidi P (2014) A review of the application of the MUSLE model worldwide. *Hydrol Sci J* 59(2):365–375
- Sánchez-Escobar F, Coq-Huelva D, Sanz-Cañada J (2018) Measurement of sustainable intensification by the integrated analysis of energy and economic flows: Case study of the olive-oil agricultural system of Estepa, Spain. *J Clean Prod* 201:463–470
- Santisteban LD, Casali J, López JJ, Giráldez JV, Poesen J, Nachtergaele J (2005) Exploring the role of topography in small channel erosion. *Earth Surf Process Landf* 30(5):591–599
- Santoni M, Ferretti L, Migliorini P, Vazzana C, Pacini GC (2022) A review of scientific research on biodynamic agriculture. *Org Agric*. <https://doi.org/10.1007/s13165-022-00394-2>
- Santos SA, Cabanas JE, Pereira JA (2007a) Abundance and diversity of soil arthropods in olive grove ecosystem (Portugal): effect of pitfall trap type. *Eur J Soil Biol* 43(2):77–83
- Santos SA, Pereira JA, Torres LM, Nogueira AJ (2007b) Evaluation of the effects, on canopy arthropods, of two agricultural management systems to control pests in olive groves from north-east of Portugal. *Chemosphere* 67(1):131–139
- Shakesby RA (2011) Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth Sci Rev* 105(3–4):71–100
- STELLA (2010) STELLA 9.1.4. Dynamic System Software. Isee System Inc. <https://www.iseesystems.com/store/products/stella-online.aspx>. Accessed 07 Dec 2022
- Uri ND (2000) Agriculture and the environment—the problem of soil erosion. *J Sustain Agric* 16(4):71–94
- van Leeuwen CC, Cammeraat EL, 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 Policy* 83:174–186
- Van Wesemael B, Mulligan M, Poesen J (2000) Spatial patterns of soil water balance on intensively cultivated hillslopes in a semi-arid environment: the impact of rock fragments and soil thickness. *Hydrol Process* 14(10):1811–1828
- Villa M, Santos SA, Sousa JP, Ferreira A, da Silva PM, Patanita I, Ortega M, Pascual S, Pereira JA (2020) Landscape composition and configuration affect the abundance of the olive moth (*Prays oleae*, Bernard) in olive groves. *Agric Ecosyst Environ* 294:106854
- Wilson C, Kampf SK, Wagenbrenner JW, MacDonald LH, Gleason H (2021) Hillslope sediment fence catch efficiencies and particle sorting for post-fire rain storms. *Earth Surf Process Landf* 46(1):267–279
- Wischmeier WH, Smith DD (1960) A universal soil-loss equation to guide conservation farm planning. *Trans 7th Int Congr Soil Sci* 1:418–425
- Wischmeier WH, Johnson CB, Cross BV (1971) A soil erodibility nomograph for farmland and construction sites. *J Soil Water Conserv* 26:189–193
- Zuazo VHD, Pleguezuelo CRR (2009) Soil-erosion and runoff prevention by plant covers: a review. *Sustain Agric*. [https://doi.org/10.1007/978-90-481-2666-8\\_48](https://doi.org/10.1007/978-90-481-2666-8_48)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.