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RESEARCH ARTICLE

Application of a dynamic model using agronomic and economic data to evaluate the sustainability of the olive grove landscape of *Estepa* (Andalusia, Spain)

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Abstract

Context In the Andalusia region (Spain), olive grove agro-systems cover a wide area, forming social-ecological landscapes. Recent socioeconomic changes have increased the vulnerability of these landscapes, resulting in the abandonment and intensification of farms. The provision of the main ecosystem services of these landscapes have thus been degraded.

Objectives To analyse the sustainability of an olive grove social-ecological landscape in Andalusia. Specifically, to develop a quantitative model proposing land planning and management scenarios, considering abandonment, production and economic benefits of olive crops in different conditions of erosion and management.

Methods We applied a dynamic model using agronomic and economic data, to evaluate different types of olive management. We considered different levels of erosion, the loss of production related to this erosion, and useful life spans for each type of management. We simulated scenarios for the long-term assessment of dynamics of crops, abandonment rate, production and benefits.

Results (a) There was a loss of productive lands and benefits in the medium term in the more intensive crops. (b) Scenarios that partially incorporated ecological management proved to be more sustainable without economic subsidies. (c) The spatial combination of integrated, intensive and ecological plots was sustainable, and was well balanced from an economic, productive and ecological point of view.

Conclusions Scenarios that partially incorporate ecological management allowed the best economic and environmental balance. However, to ensure the sustainability of olive landscapes, farmers should be financially rewarded for their role in the conservation of ecosystem services through landscape stewardship and direct environmental payments.

Keywords Common Agricultural Policy · Landscape services · Management scenarios · Soil erosion · Sustainable olive grove management

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Introduction

Agro-systems that originated from the modification of natural ecosystems by agriculture present their own biophysical characteristics. The interconnections between agro-systems and natural ecosystems result in agricultural landscapes. Historically, in Europe, traditional agricultural landscapes were transformed from mono-agricultural systems to pluri-rural activity systems adapted to the structure and function of the landscape (Fleskens et al. 2009). In this process, a co-evolutionary relationship between social and ecological systems was established, giving rise to productive working landscapes, that is, rural cultural landscapes with land uses adapted to the local environmental conditions (Farina 2000). This slow co-evolution led to a mutual adaptation among abiotic, biotic and cultural factors, forming complex adaptive social–ecological systems. These systems are characterised by cross-scale, non-linear interactions and feedback loops between the ecological and socio-economic components and by their capacity for transformation and adaptation to human activities and the environment based on their resilience (Termorshuizen and Opdam 2009).

Increasing social demands to link agriculture to other land uses, and particularly to biodiversity conservation, has given rise to the concept of multi-functionality to support sustainable agriculture, especially in Europe (Huang et al. 2015). This concept was introduced to overcome the purely productive concept (food and raw materials) of agriculture, appealing to two more dimensions of this activity: its environmental function, related to the protection of the environment, natural resources, ecosystems and agricultural landscapes; and its social function, related to its value in generating territorial cohesion and preserving the socio-economic fabric of rural areas. The findings of the Millennium Ecosystem Assessment (MA 2005) on the pervasive impacts of agriculture on all of Earth's ecosystems, led to a shift in the idea of the multifunctional role of agriculture towards a more integrated approach focusing on the concept of multifunctional landscapes as providers of environmental, social and economic functions (Reyers et al. 2012). The multi-functional agricultural landscapes would then play a critical role in providing products for human well-being, supporting wild species biodiversity and maintaining ecosystem services (ES) (O'Farrell and Anderson 2010). Moreover, the assumption of agricultural landscapes as resilient complex adaptive social–ecological systems under the ES framework, allowed for the realignment of the concept of multi-functional landscapes to social-ecological landscapes (SELs) as providers of multiple ES (Matthews and Selman 2006; Rescia and Ortega 2018). More specifically, the concept of SEL refers to a production landscape where the driving force of its dynamics is productive land use. Therefore, its dynamics can best be understood in the context of a complex adaptive socio-economic and ecological system, assuming the scale and spatial pattern of human land uses (Zaccarelli et al. 2008). Its sustainable management must occur at that socio-ecological scale to adjust the scale of the ES demand (socio-economic) and the scale at which the ES provision can be ecologically sustainable (Cumming et al. 2013). In this context, the economic function of SELs is determined by the provisioning ES, the social function by the cultural ES and the environmental function by the regulating ES. Their resilience consists of ensuring the flow of these ES (Huang et al. 2015).

A paradigmatic example of SELs are olive groves, which act as marked multi-ES providers (Rodríguez-Entrena et al. 2014). These ES include the production of olive oil and olives (provisioning), improvement of air quality and carbon sequestration capacity (regulation), and a sense of place and traditional ecological knowledge (cultural). The relevance of olive grove SELs in the Mediterranean region is widely recognised (Torres-Miralles et al. 2017). In Spain, this is evidenced by the country's status as the world's leading producer of olive oil, more than 1.2 M t^{-1} -year^{-1}; their wide territorial coverage, more than 2.5 M ha (1.5 M in Andalusia region, southern Spain); and the numbers of people employed in this industry, with more than 10% of the agricultural sector employed in these crops or related activities representing more than 6% of national agrarian income (20% in Andalusia) (INE 2014). However, in recent years, global and regional socioeconomic changes have resulted in a vulnerable situation for these SELs due to the loss of viability of exploitations. This loss has been caused by the uncertainty of production and the volatility of prices, highly dependent on the annual harvest, and the low-price competitiveness of their products, which is reflected in a low profitability.

The vulnerability of olive grove SELs in the Andalusia region is leading to the abandonment of many olive farms and a sharp intensification (Duarte et al. 2008). Farm abandonment entails a loss of cultural ES and the degradation of social stability (Mann and Wüstemann 2008), along with the total loss of profitability. The abandonment of farming systems also causes a disruption in regulating services (i.e. disservice) by increasing biomass (i.e. scrub encroachment), thus enhancing the risk of fire. In turn, the intensification process (mechanisation, irrigation, increase in planting density, monoculture, use of agro-chemicals) makes it possible to increase agricultural production by improving the profitability of olive groves. However, at the same time, it causes environmental problems, especially affecting regulating ES, such as the acceleration of erosion and higher levels of diffuse terrestrial and atmospheric pollution (López-Pintor et al. 2018). The effect on biodiversity after abandonment is unclear, while intensification has a negative impact on this parameter, which is a potential generator of ES (Flohre et al. 2011).

The importance and severity of erosion is increasing at a global scale. In Europe, more than 115 M ha are affected by soil erosion. This is particularly noteworthy in the Mediterranean region where more than one-third of agricultural lands presents erosion greater than 15 t ha^{-1} $year^{-1}$, because of the fragile environmental conditions (hydric stress and torrential rains). In Spain, 35% of the territory presents erosion problems (a loss of soil greater than 12 t ha^{-1} $year^{-1}$, mainly on the Mediterranean side) and in Andalusia, 70% of agricultural land is classified with a medium to high risk of erosion (González 2003). ICONA (1991) estimated that the direct costs of erosion in Spain were around €280 M, and the costs of mitigating its effects reached €3000 M for a period of around 20 years. Particularly, soil erosion is a key factor in olive grove production, directly affecting profitability (Gómez et al. 2014a). However, information about erosion and its relationship to production and profitability remains limited and further efforts are required to identify erosion prevention strategies.

Considering the situation of the olive groves in Andalusia and their regional and global importance, a quantitative analysis of their current management and a possible alternative management model at a landscape scale is needed (Fleskens et al. 2009). This should be oriented towards guaranteed olive grove sustainability (persistence) and their social-ecological resilience (maintenance of flux of ES), based on economic profitability, social stability and environmental conservation. In other words, a landscape management approach focused on the provision of ES in the long-term is required (Termorshuizen and Opdam 2009). Many of the studies of olive landscapes in the Mediterranean that have analysed their ecological characteristics (D'Imperio et al. 2007), or their economic and cultural features (Ferguson 2006), lack an integrated (combining regulating, cultural and provisioning ES) and dynamic approach. In this study, an olive grove area in Andalusia was analysed as a multi-ES SEL (spatially, the olive crop agro-system and its surrounding land uses), applying a dynamic model to assess sustainability and resilience. The specific objectives were: (a) to develop a conceptual management model; (b) to quantify the components of the model; (c) to analyse land planning and management scenarios for the olive crops, evaluating abandonment, production and economic benefits, and considering, essentially, different levels of soil erosion.

Methods and data processing

Study area

The study area covers an olive grove SEL in the Andalusia region (Fig. 1). This area corresponds to the Protected Designation of Origin (PDO) of extra virgin olive oil of *Estepa*, that produces 30 M kg of olive oil per year, half of the total production of the province of Seville, representing 5500 farmers and 19 associated mills (BOJA 2015; Oleoestepa 2018). Olive groves cover 70% of the total area and their products generate an income of €225 M and 224,000 daily wages (close to 10% of the daily wages of Seville), considering only activity in the field (INE 2018). In all municipalities in the area, olive production and daily wages dedicated to olive groves exceed 50% compared to other productive activities (BOJA 2011, 2015). Specifically, the PDO presents almost 40,000 ha of olive groves, predominantly managed in an integrated manner (considered as semi-ecological because the use of agro-chemicals and machinery is regulated) and 20,000 ha of other land uses with less than 10% of natural or semi-natural vegetation (Rescia et al. 2017).

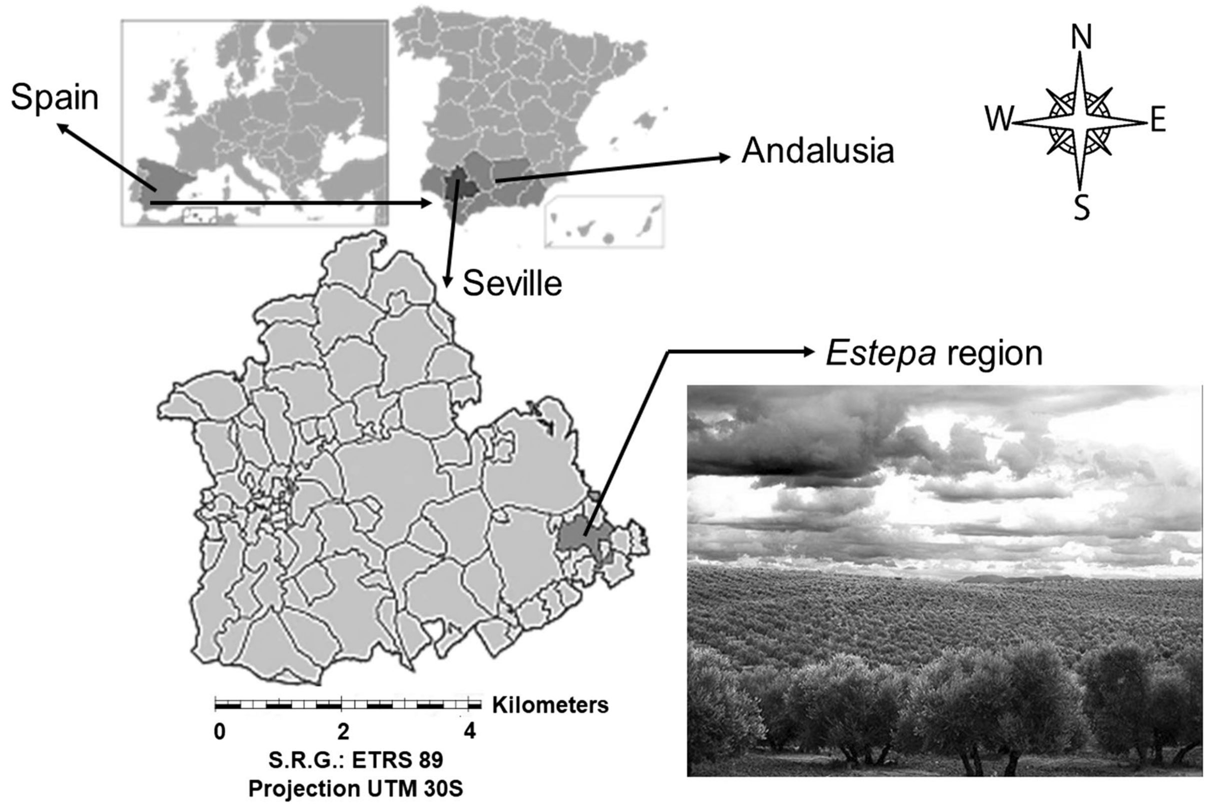


Fig. 1 Location and partial view of the agricultural landscape of *Estepa*

Most of the olive groves are under a rain-fed regime but, in several cases, they are subject to deficit irrigation (only when there is hydric stress). The climate is Mediterranean with an annual average temperature of 17.5 °C and annual average rainfall of 477 mm. The main type of soil is clay-sandy (*Albariza* type, with calcareous material predominant) and the olive groves are considered plain crops since the average altitude of the region is between 200 and 800 m.a.s.l.

Assumptions and schematization of the conceptual model of olive grove management

The conceptual model developed is based on data related to characteristics and management of olive crops from different studies, direct consultations with experts and potential users (farmers, technicians, soil scientists, economists) and field data from *Estepa* and official statistical data at the local and regional levels (AEMO 2012; BOJA 2015; EUROSTAT 2017; MAPAMA 2017; POOLred 2017). These experts and potential users have also examined and validated the model. The assumptions of the model were: (a) any olive crop management is currently subject to subsidies from the Common Agricultural Policy (CAP), as ancestral permanent woody crops; (b) all of the olive groves in the studied region are managed in an integrated manner; (c) different degrees of agricultural intensification were implemented in the model, differentiating intensive from highly-intensive management, with different densities of plantation (200–600 and 1000–2000 trees/ha, respectively) and correspondingly useful life spans (temporary term in which the agro-system ceases to be profitable and must be abandoned) of 40 and 15 years (AEMO 2012; Connor et al. 2014). This characterisation of intensive or highly-intensive management (olive groves in hedges, fundamentally), based exclusively on tree density, is a hyper-simplification of the concept of intensification. This single factor criterion is based on that applied by the technicians, managers and farmers of the *Estepa* region for their olive groves (Caballero, personal communication, May 22, 2018), since the intensification due to the inputs (fertilizers, pesticides, herbicides) applied to the olive grove is controlled in such a way that it falls under the requirements considered in the integrated management. In other words, 30% of the integrated olive crops of *Estepa* would be intensive due to the density of trees, but not based on external inputs or practices and thus, it is assumed in this study as non-intensive management.

Other relevant considerations in the elaboration of the model were: (a) average production between 1500 and 4000 kg of olive ha^{-1}, assuming an abandonment of the crop below the lower value of this range (following the criterion of Gómez-Calero 2010); (b) existence of a progressively accelerated decrease in production over time (Lal 2001), based on a linear loss of soil by erosion and an asymptotic relationship between production and soil depth (Gómez et al. 2014a); (c) no action to recover abandoned or feral lands (Caballero, personal communication, May 22, 2018), thus assuming a permanent abandonment; (d) a broad simulation period of 150 years was used, which is what is required to adequately demonstrate the consequences on erosion, production and profitability of the different types of management analysed (but not including changes that can be foreseen in both olive grove management as well as in the CAP). In addition, the natural alternating production of olive groves (*vecería*, Aguilera and Valenzuela 2012) was not considered, since in *Estepa* this phenomenon is minimised by different agricultural practices and the socio-productive stability that implies the regional level management of the unique cooperative of *Oleoestepa* (Caballero, personal communication, May 22, 2018).

The simulation model developed combines an agronomic module with an economic module allowing the analysis of the dynamics of changes in land use and olive production (Fig. 2). In the agronomic module, the current agricultural production of the crops was reflected, classifying the lands (parcels or plots) where they are located according to their erosive state. In turn, the abandonment of crops was assumed by the decrease in production due to erosion and, in specific cases such as intensive and highly-intensive crops, to the end of its useful life. The scenario simulation included the transition of lands from integrated management to any other type of management, including the possible transformation of olive groves to ecological or organic management. In the economic module, the annual production of olive groves (kg ha^{-1}) transformed into olive oil (l ha^{-1}) was considered. Additionally, the costs and income of the crop production were reflected, considering the current subsidies of the CAP, and thus obtaining the benefits of the exploitation.

Implementation of the olive grove management simulation model

We used the modelling and simulation software STELLA (STELLA 9.1.4 ® STELLA 2010; Online Resource 1). To implement the model, the initial olive groves were classified into four categories according to their conditions of erosion: (a) null; (b) slight; (c) moderate and (d) severe. Categories (b) to (d) present a production decrease over time due to the loss of soil by erosion, which was implemented mathematically according to the model of Gómez et al. (2014a), adapted and calibrated specifically for the *Estepa* region:

$$Production_{(t)} = P_i \cdot \left(c_1 + c_2 \cdot ln\left(W_j - Er_j \cdot t\right) + c_3 \cdot \left(\ln\left(W_j - Er_j \cdot t\right)\right)^2\right), \quad (1)$$

where $Production_{(t)}$ production of management i in time t (t ha^{-1}); c_1, c_2 and c_3 site specific constants depending on the average rainfall and soil type, being 0.7388, − 0.3471 and 0.0401, respectively; P_i initial (t = 0) production of management i (t ha^{-1}); W_j soil weight of the erosive category j; Er_j soil loss rate of the erosive category j; t simulation time.

In turn, the abandonment of crops was assumed when production falls below the stipulated minimum threshold. All feral lands were collected at their own level, with their extent quantified at the end of the simulation. We also calculated the total annual production, in both kg of olives and liters of olive oil, considering the total area cultivated with olive crops. The annual production (l ha^{-1}) was applied as the basis for which the total incomes were calculated through the price of olive oil at source (€ l^{-1} and referred to the area), incorporating the CAP subsidies. Additionally, the total operating costs (including personnel and machinery) were calculated considering the total area cultivated with olive crops. Finally, determining the difference between incomes and costs, we obtained the total annual benefits (€ ha^{-1})

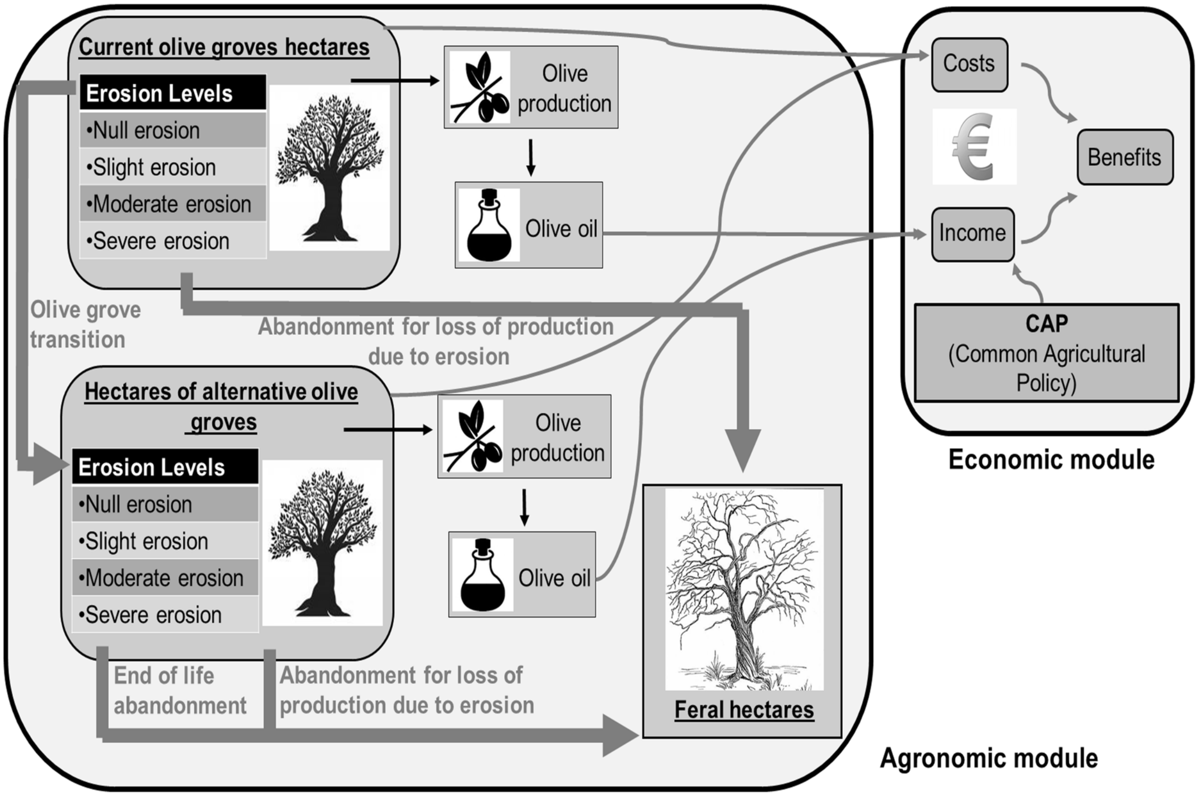


Fig. 2 Conceptual model of the dynamics of olive grove management that combines an agronomic module of land dynamics with an economic module

of olive groves in the study area. The economic and production data used for the model are based on specific data from *Estepa*, when they were available, and on the most often applied official sources for these types of studies (mainly AEMO, POOLred). This information is private and highly sensitive and, in many cases, the data supplied are fragmented and unreliable. Therefore, we tried to combine the specific data from *Estepa* with the generic (official) data, finding in general a good agreement between the two sources.

Calibration of the conceptual model: current situation

Table 1 shows the area of different levels of erosion and the values of factors that determine the potential loss of soil for the studied area. We considered 39,463 ha of olive crops, establishing a classification according to different levels of erosion based on the (BOJA 2015) classification. The potential annual rate of loss of soil was calculated following the Revised Universal Soil Loss Equation (RUSLE model) (Wischmeier and Smith 1960; Diodato 2006):

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P, \quad (2)$$

where the value obtained is the loss of soil, A, based on the rain erosivity, R; the soil erodibility, K; the length and grade of the slope of the territory, L, S; the ground cover, C; and the agricultural conservation practices, P. To calculate the values of A it was necessary to know the soil weight W_j, which was estimated from experimental data from *Estepa* using Eq. 3 (Moreira-Madueño 1991):

$$W_j = 100 \cdot h_j \cdot appd_j, \quad (3)$$

where W_j soil weight (t ha^{-1}); h_j soil depth (cm); $appd_j$ apparent density of the soil (g cm^{-3}).

In this way, for the non-eroded lands, *appd* was 1.11 g cm^{-3}, h was 141.7 cm, and W was 15,728.70 t ha^{-1}; with slight erosion, *appd* was 1.12 g cm^{-3}, h was 124.3 cm, and W was 13,921.60 t ha^{-1}; with

Table 1 Characterisation of the olive grove areas according to their type of management and their level of erosion. Estimation of erosive rates (A) and the number of hectares (ha; %) for the initial situation are detailed (integrated management). In addition, erosive rates are estimated in the generated simulation scenarios (intensive, highly-intensive and ecological management). The LS factor is dimensionless and is expressed as a percentage; the C factor, dimensionless, should only be considered 1 for bare soils; and value of the P factor, dimensionless, is 1 when agricultural practices are present and 0 when they are not (for further details, see the text)

Management type	Erosion level	Olive grove area (ha (%)) (initial situation)	Factors					A (t ha^{-1} $year^{-1}$)
			R (J ha^{-1})	K (Mg J^{-1})	LS	C	P	
Integrated	Null	22,494 (57.00)	109.7	0.82	0.00 (0%)	0.16	1	–
	Slight	8366 (21.20)	109.7	0.89	0.18 (3%)	0.16	1	2.81
	Moderate	3828 (9.70)	109.7	0.56	0.70 (7%)	0.16	1	6.88
	Severe	4775 (12.10)	109.7	0.95	2.20 (15%)	0.16	1	36.68
Intensive	Null		109.7	0.82	0.00 (0%)	0.33	1	–
	Slight		109.7	0.89	0.18 (3%)	0.33	1	5.80
Highly-intensive	Null		109.7	0.82	0.00 (0%)	0.09	1	–
	Slight		109.7	0.89	0.18 (3%)	0.09	1	1.58
Ecological	Null		109.7	0.82	0.00 (0%)	0.06	1	–
	Slight		109.7	0.89	0.18 (3%)	0.06	1	1.05
	Moderate		109.7	0.56	0.70 (7%)	0.06	1	2.58
	Severe		109.7	0.95	2.20 (15%)	0.06	1	13.76

moderate erosion, *appd* was 1.20 g cm^{-3}, *h* was 109.5 cm, and *W* was 13,140.00 t ha^{-1} of soil; and with severe erosion, *appd* was 1.34 g cm^{-3}, *h* was 69.2 cm, and *W* was 9272.80 t ha^{-1} of soil. The increase in density as the erosive state progresses is related to the calculation of bulk density, that is, dry soil mass divided by the initial volume of the sample. The taking of soil samples with a fixed volume core (141.37 cm^3), together with the increase in soil compaction and the decrease in porosity as erosion increases, gives rise to a larger edaphic mass within the same volume (Helson et al. 2017).

The values of the factors of the RUSLE equation were taken mainly from Moreira-Madueño (1991), Gómez et al. (2003), Gómez and Giráldez (2010) and Sánchez Escobar (2015) and our own experimental data. In this sense, the K value of soil erodability was calibrated experimentally using Eq. 4 (Gisbert Blanquer et al. 2012):

$$K = \left[\left[10^{-4} \cdot 2.71 \cdot M \cdot (12 - a)\right] + 4.2 \cdot (b - 2) + 3.2 \cdot (c - 3)\right] \cdot 100^{-1}, \quad (4)$$

where *M* representative factor of soil texture (100-% clay) * (% silt + sand); *a* organic material (%, in the *Estepa* region, this value is assumed as 1); *b* soil structure code; and *c* soil permeability code; *b* and *c* codes according to the nomograph of Wischmeier and Smith (1978). These values were experimental and taken from SEISnet (2018).

On the other hand, factor C was calibrated for *Estepa* according to the criteria in Gómez et al. (2003). In this way, factor C varies with the type of management depending on tree density (minimum in both integrated and ecological managements), canopy diameter (minimum at highly-intensive management), and with the extent (width) of ground covers (null in intensive crop, medium in integrated and highly-intensive, and maximum in ecological). Finally, factor P was considered 1 for all erosion situations as it was assumed that all plots are subject to tillage practices and yet none are subject to specific mechanical or soil manipulation erosion control practices (ploughing parallel to contour lines, terraces, structures and holding dams or others (Gómez and Giráldez 2010; Sánchez Escobar 2015), regardless of ground cover as an agronomic measure considered in factor C.

While transition of hectares of all erosive states was taken into account for the generation of an ecological management scenario, to generate the intensive and highly-intensive management scenarios only the possible transition of hectares with null or a slight erosive state was considered, thus not promoting the intensification in plots with high erosion. Table 2 shows the production and economic data considered according to the olive management applied by farmers.

Finally, the amount considered for the subsidies of the CAP received by the farmers for any type of olive management was 1.05 € l^{-1} for olive oil produced, following (AEMO 2012).

Spatial land planning and management scenarios

We considered a mechanised and mostly rain-fed integrated management for the current situation of olive groves (‘business as usual’ scenario (a)), (Egea and Pérez 2016). A series of scenarios of partial changes in crop management types were simulated, where the transition of lands from one type of crop to another was implemented over a decade and carried out in a uniform way for a predetermined amount of 10% of the land (ha) of the base management to another type of olive management according to the proposed scenario. The proposed scenarios (Fig. 3) were: (b) transition to intensive management; (c) transition to highly-intensive management; and (d) transition to ecological (i.e. organic) management. Intensification prioritises production over environmental impacts and organic farming minimises environmental impacts, maintaining productive levels close to those of integrated management (Francia Martínez et al. 2006). A scenario of mixed management at the landscape scale was also proposed (e), through a spatial combination of crops (land planning considering the pattern of land use and ground cover), in which a transition was made to intensive and ecological (5% of the initial area, respectively) management, attempting to balance the priorities between production and profitability. Within these new management scenarios, in addition to the loss of crops (ha) due to the fall of production from erosion, the useful life of each type of management was implemented in the model when necessary, at the end of which the total and permanent abandonment of the crop was assumed.

The typical methodology of scenario planning consists of using a few contrasting scenarios to explore the uncertainty surrounding the future consequences of a decision (Peterson et al. 2003). In this study, we aimed to show the most contrasting situations of olive grove management (highly-intensive vs. organic), and intermediate and continuity situations. The highly-intensive management would be a priori greatly conditioned by the specific climatic, ecological, soil and other factors in *Estepa*, but the existence of two farms (about 15 ha) with this treatment in the region led us to consider that this type of management will be taken up by some farmers in the near future. Nevertheless, with the aim of being realistic, we restricted the transitions to more intensive

Table 2 Annual production, sale price of olive oil and annual costs for the different types of management considered. Values taken from (AEMO 2012), (POOLred 2017) and information from Estepa based on Caballero (personal communication, May 22, 2018)

	Integrated	Intensive	Highly-intensive	Ecological
Production (kg/ha)*	3500	5000	10,000	3500
Sale price of olive oil (€/l)	2.64	2.00	1.58	4.49
Costs (€/ha)	1785	1894	2366	1057

*One l of olive oil is obtained from 5.26 kg of olives. 19% yield crop (Caballero, personal communication, May 22, 2018)

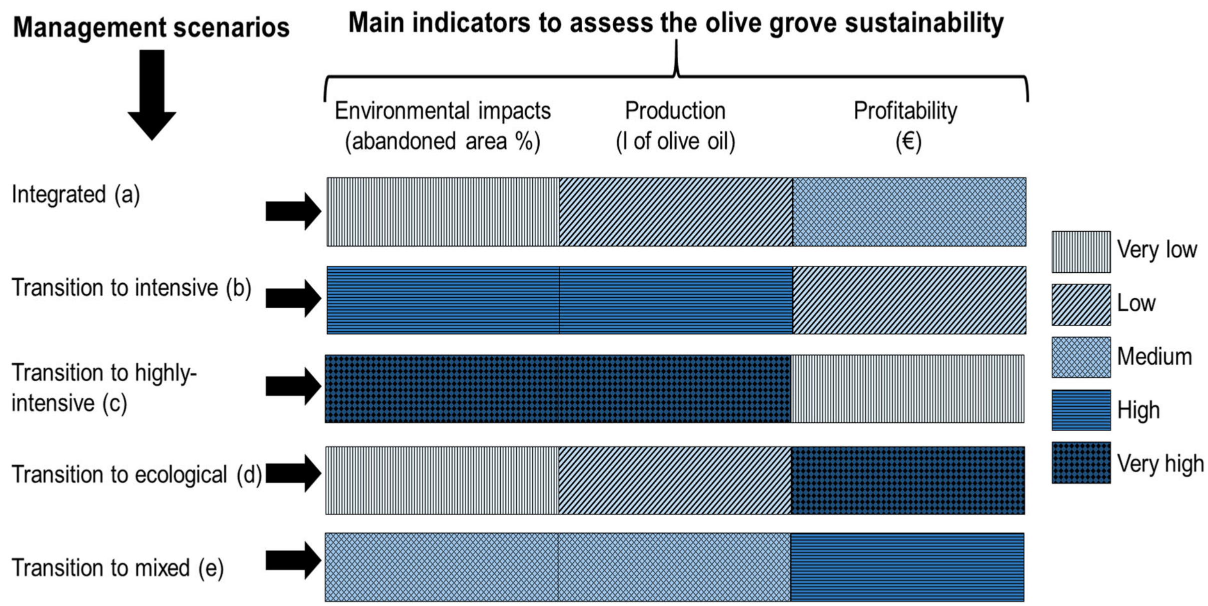


Fig. 3 Graphic representation of the proposed scenarios showing their qualitative implications around the three main indicators to assess the sustainability of the olive groves: (1) environmental impacts; (2) production; and (3) profitability

management to adequate areas (with null or slight erosion).

Results

Dynamic simulation for different scenarios of spatial land planning

Accelerated soil erosion as an environmental constraint

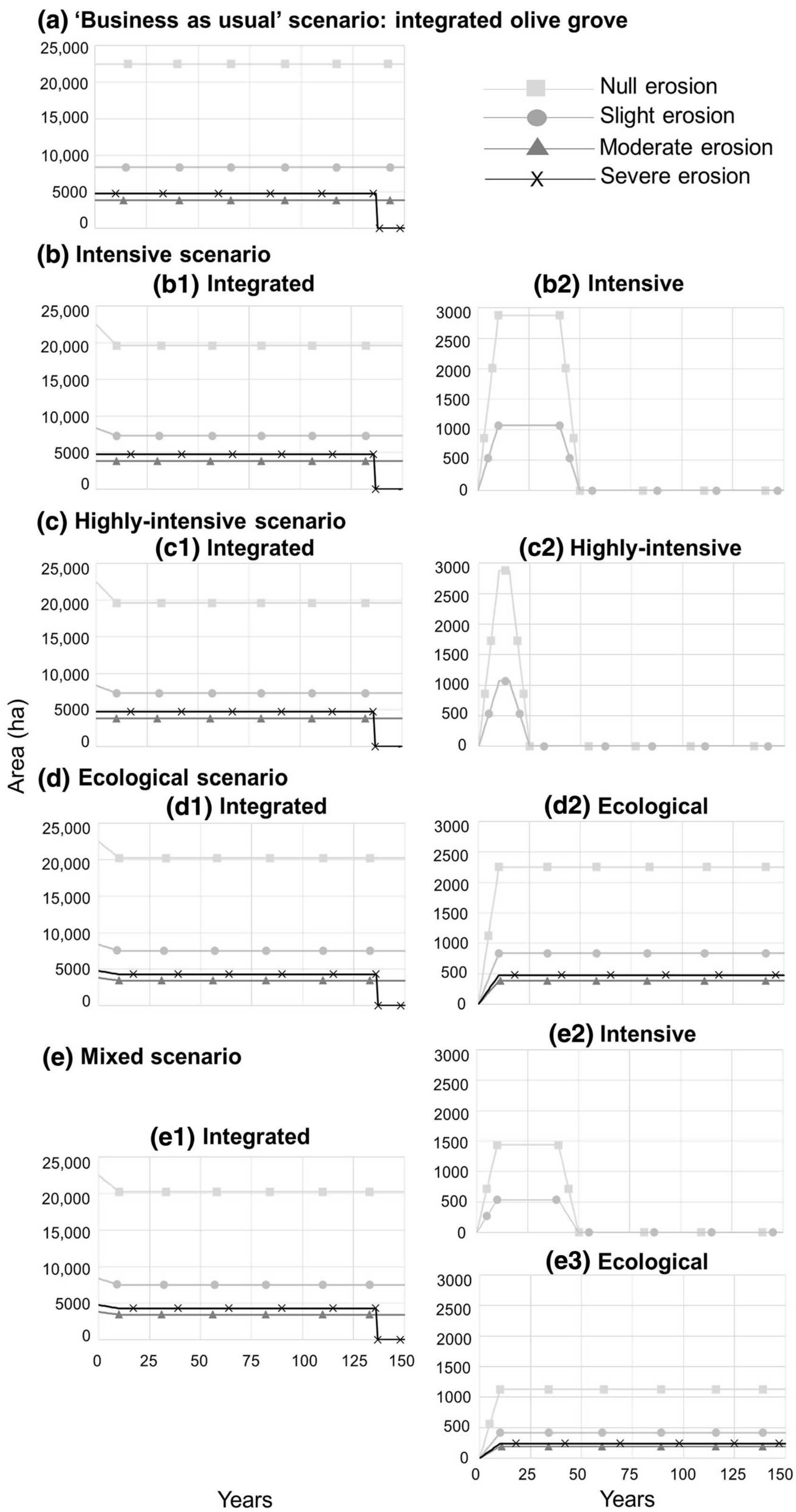
Dynamic analysis regarding the evolution of olive groves according to these erosion situations, maintaining the current ('business as usual') integrated olive management, showed a tendency towards early abandonment of those crops with severe erosion (approximately 135 years after the start of the simulation; Fig. 4a). There is no expectation of abandonment of the lands with any other level of erosion in a reasonably longer period and thus, the continuity of agricultural practices can be considered viable in those plots in the long term. The figures of integrated management in the transition scenarios (Fig. 4b1, c1, d1, e1) only show small differences depending on whether restrictions are applied to the transformation of lands with higher levels of erosion, according to the assumptions of each scenario.

Results regarding the transition scenarios towards intensive and highly-intensive management practices, showed a tendency towards the complete abandonment of the agricultural system in a relatively short term (50 and 25 years, respectively; Fig. 4b2, c2), according to the assumptions made and the information currently available about the system. The loss of productive lands based on the useful life of the crops (which integrates the combination of impacts and biological, physical and economic factors that compromise the viability of these crops) under these types of management would be the main cause of abandonment.

The partial transition scenario towards a greater presence of ecological crops, unlike the case of integrated management, shows that the severe eroded areas are not lost within the time simulated, based on better soil protection under ecological management (Fig. 4d2).

Finally, we observed the dynamics for the mixed-management scenarios that spatially combine the integrated crops with a lower proportion of intensive (Fig. 4e2) and ecological management (Fig. 4e3). That is, we proposed spatial planning based on

Fig. 4 Different scenarios of the evolution of the olive groves considering their different levels of soil erosion. 'Business as usual' scenario (**a**); partial transition scenarios towards intensification practices, including intensive (**b**) and highly-intensive (**c**) management; ecological management (**d**); and a mixed scenario (**e**) that combines integrated management (*e1*) with intensive (*e2*) and ecological (*e3*) management. The different patterned lines represent the erosion levels: null; slight; moderate and severe



patterns of mixed management (i.e. agricultural mosaic with different types of management).

Land abandonment, production and profitability

We evaluated the level of crop abandonment, as an environmental indicator, for the different scenarios of management (Fig. 5a). In addition, the production (Fig. 5b), along with the benefits for each scenario, was also analysed. The benefits were valued in two different situations: a) without considering the subsidies of the CAP received by farmers and b) considering these subsidies (Fig. 5c1, c2).

Specifically, Fig. 5a shows that the ecological and integrated management of olive groves led to a lower rate of abandonment (11 and 12% of the total area occupied by olive groves, respectively) while intensive management would force a greater proportion of farmers (22% of the olive-growing area) to abandon their farms due to a lack of productivity of their plots. Therefore, scenarios with more environmentally friendly management of olive groves would allow a greater persistence of these plantations in the long term. A scenario in which integrated and organic management approaches were mostly combined presented a somewhat lower abandonment rate than intensive management but higher than exclusive integrated or ecological management (17% of abandoned or feral lands).

The annual production analysis of the scenarios showed that the scenarios with higher production over time are those of ecological and integrated management

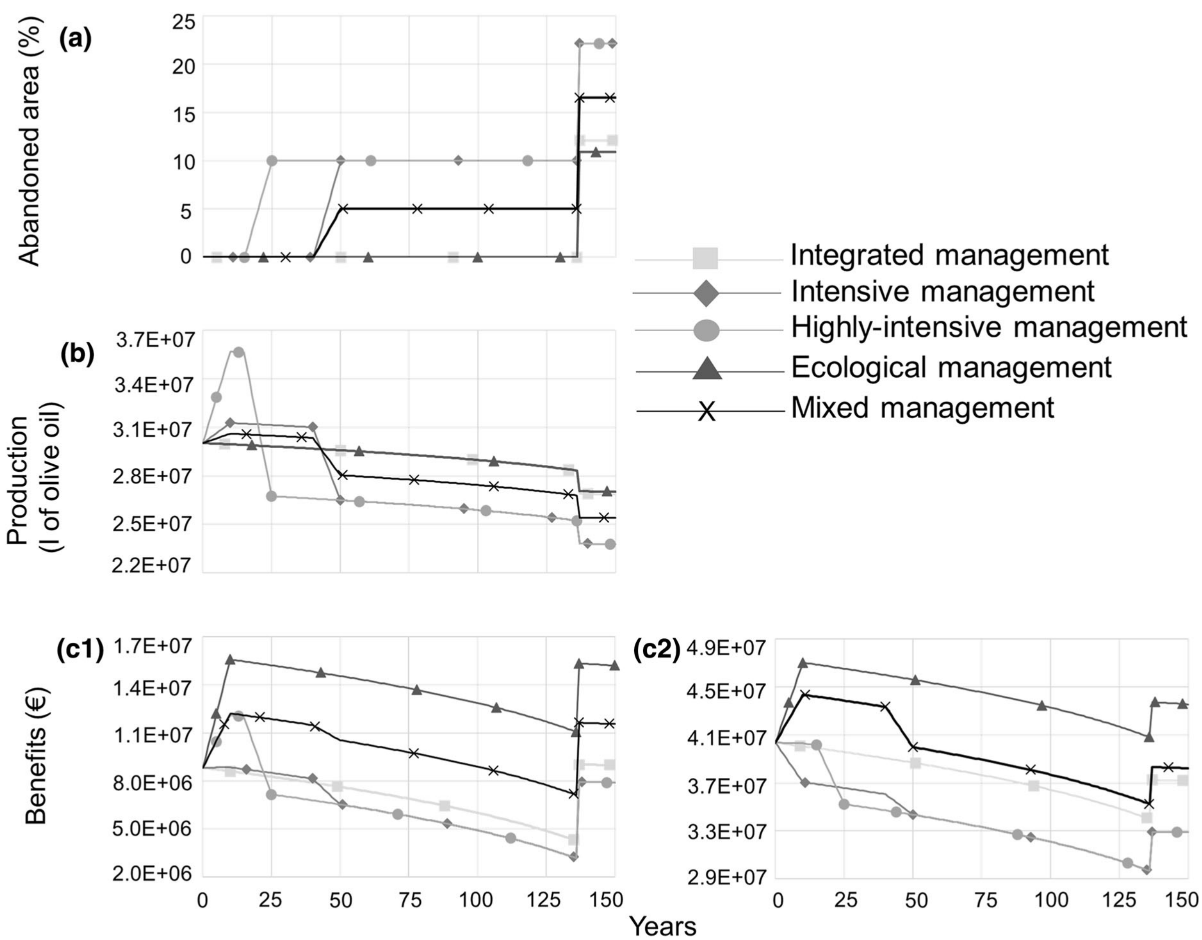


Fig. 5 Total abandoned lands (**a**), olive oil production (**b**) and benefits with and without subsidies of the Common Agricultural Policy (*c1* and *c2*, respectively). The different patterned lines represent scenarios based on integrated management; transition to intensive management; transition to highly-intensive management; transition to ecological management and proposed mixed management scenario

(around 27 M l of olive oil; Fig. 5b). The final production level of the mixed management scenario is intermediate (25 M l of olive oil). It is possible to appreciate the presence of a higher productivity level at the beginning of the simulation for the intensification scenarios, highlighting the presence of an early peak of maximum production with highly-intensive management. However, this becomes transitory due to the rapid loss of arable land and biological limitations under this management approach, leading to, in general terms, a progressive decrease in production over time until values lower than the rest of the scenarios are reached (approximately, 24 M l of olive oil). Regarding the economic dimension, it is interesting to evaluate the economic performance without incorporating the subsidies of the CAP, since the support of this source is a recurrent uncertainty each time it has to be renewed. Figure 5c1 shows that, without CAP subsidies, the intensification scenarios reach the lowest levels of benefit in the medium term, progressively approaching non-profit thresholds as erosion decreases productivity and compromises the sustainability of highly eroded areas. On the contrary, the scenario with ecological management shows the highest viability, followed by the mixed scenario. When incorporating these subsidies into the model, the ranking order of profitability for the different types of olive management does not change, and the relative contribution to the benefits of early increased productions of more intensive olive groves becomes even less remarkable (Fig. 5c2).

Finally, it can be seen, from the data on production, as well as economic benefits accumulated throughout the simulation time (Table 3), that in both terms, the scenarios corresponding to the intensification practices are the most unprofitable in the long term. Additionally, the scenario with ecological management, even with a production level equal to that of the integrated crop, reaches the highest profitability because of the better price of organic olive oil, whereas the mixed exploitation strategy remains at an intermediate level.

Discussion

Environmental constraints

The direct effect of erosion (technically, accelerated soil erosion due to agricultural practices) is the reduction in, or even lack of, crop yields. In severe cases, this would be irreversible, having an important economic impact. In terms of production, based on statistics from (FAO 1995) and Lal (2001) estimated a loss of more than 10% of world food production due to soil erosion. In economic terms, the estimation of the total cost of soil erosion was U$45 billion year^{-1} at the European level (Montanarella 2007), and U$5–66 ha^{-1} year^{-1} in a case study in Spain (Hein 2007). The results in *Estepa* showed that olive grove production and the benefits for farmers were highly affected by accelerated soil erosion. Our results showed that, for integrated and intensive scenarios, a loss of 12–22% of arable land can lead to economic losses of about €5–6 M. As a result of this production/economic impact, farmers in many cases abandon their exploitations or intensify their farming practices. Several studies have shown that in arable lands, soil erosion is aggravated by both abandonment and intensification (in many cases associated with irrigation in sloping areas) (García-Ruiz and Lana-Renault 2011). However, in the case of *Estepa*, where agricultural land uses are predominant, the abandonment of lands with severe problems of erosion would probably be beneficial to certain regulating ES, such as carbon sequestration and soil formation or retention. In olive crops, it has been estimated that appropriate agricultural practices enhance soil retention and especially carbon sequestration (Mohamad et al. 2016). In addition, in unharvested feral plantations, a high diversity of wildlife (especially birds and pollinators) and the persistence of their landscape structure (Beaufoy 2001) has been observed.

Colacicco et al. (1989) estimated that the on-farm cost of soil erosion was half of the off-site costs. This fact implies that on-site costs (i.e. farm scale) affect the production units directly, provisioning-economic and cultural ES essentially, while off-site costs (i.e. regional and global scales) have an impact on the environment, economy and society, mainly affecting regulating and provisioning ES. Considering these impacts, the importance of conserving the agronomic productivity of agricultural lands is vital for food security and economic viability. Additionally, a pressing problem for the SEL of olive groves, which deserves increasing attention, is the effect and possible consequences of climate change for these landscapes. The Mediterranean region, where 95% of the olive groves are concentrated, will be particularly affected

Table 3 Accumulated production and benefits, without and with CAP's subsidies, throughout the simulation time for the different management types considered

	Integrated	Intensive	Highly-intensive	Ecological	Mixed
Accumulated production (l of olive oil)	4.37E+09	4.10E+09	4.05E+09	4.37E+09	4.23E+09
Accumulated benefits without CAP (€)	1.07E+09	9.62E+08	9.78E+08	2.05E+09	1.51E+09
Accumulated benefits with CAP (€)	5.65E+09	5.08E+09	5.09E+09	6.64E+09	5.95E+09

by the expected climate changes, and the rising temperature will cause a northward and eastward shift of the suitable area for olive trees (Ferrise et al. 2013). Specifically in Andalusia, some effects predicted due to the expected future climate change are the advance by several weeks in the flowering of the olive tree (Galán et al. 2005); a loss of the altitudinal gradient and the main expanse of olive groves fragmented into smaller patches (Ropero et al. 2018); and a significant reduction in precipitation along with an increase in potential evapotranspiration at the end of the century, affecting olive tree yield (Gómez et al. 2014b).

Possible management scenarios

A scenario based on a continuation of integrated olive grove management at a farm scale in the *Estepa* region, showed that a moderate proportion of olive crops would be abandoned. This abandonment of the agricultural areas is based on the increased risk of erosion altering the fertility of soil and crop yield and farmer profitability. This problem is very frequent in the Andalusian olive groves (Fleskens and Stroosnijder 2007), but in *Estepa* the current rate of land abandonment is relatively low (Rescia et al. 2017). The existence of farming practices in integrated management contributes to a reduction in the magnitude of erosion processes (Zuazo and Pleguezuelo 2009). Farmers carry out treatments (pruning and cutting) to olive trees providing organic matter to the fertile edaphic horizon and branches and leaves to protect the soil. Additionally, they often use live (natural or implanted) and even inert ground covers to mitigate soil erosion. In the transition scenario to a more agroecological olive-growing treatment, the extent of abandoned areas is similar to the integrated management scenario. The main objective of ecological management is to obtain high-quality food promoting sustainable agricultural development. This sustainability implies, as in integrated management, the maintenance of a natural or implanted ground cover and strict controls to avoid the use of agro-chemicals (Egea and Pérez 2016). The integrated and ecological scenario options, to the extent that 12% of long-term land abandonment was acceptable, could be considered sustainable and viable in *Estepa*. The scenarios proposed for both integrated and ecological options would have similar long-term abandonment rates and be more sustainable than intensive management options.

The abandonment rates in the intensive and highly-intensive scenarios were higher. These management options require high energy inputs (agro-chemicals, labour and machinery), which have serious environmental repercussions in the landscape such as accelerated soil erosion, and diffuse atmospheric and terrestrial pollution (Francia Martínez et al. 2006). The process of agricultural intensification in Europe has led to a spatial simplification of agricultural landscapes accompanied by a loss of biodiversity and a reduction in the ability of ecosystems to provide goods and services (Flohre et al. 2011). For example, as Tilman et al. (2002) highlighted, the application of fertilisers and pesticides increases nutrients and toxins in groundwater and surface waters affecting regulating and cultural ES (water purification, fisheries, recreational values and aquatic habitats). The effects on regulating ES related to aquatic aspects tend to be more severe in the Mediterranean region, with mainly poor soils and high levels of hydric stress, particularly in the olive groves. In fact, the intensification of olive groves grants greater importance to the productive level of the farm than to the environmental repercussions of land management and thus, soil protection practices are not the norm (Flohre et al. 2011).

In the proposed mixed management scenario, presenting landscape-scale management based on the spatial combination of different treatments, the proportion of feral lands in the long term is intermediate between the more ecological and more intensive options. On the other hand, it allows the maintenance of an acceptable production level, which is a logical objective of farmers (Caballero, personal communication, May 22, 2018). This type of management could meet the latest greening trends in the CAP—one of the major drivers in farming practices in Europe—to gradually favour farmers with subsidies that are subject to a certain type of spatial planning associated with environmentally-friendly forms of farming management. In fact, as shown in our model, the inclusion of the CAP subsidies increases the economic profitability of olive groves in the long term, with the scenario of ecological management standing out as the most profitable due to the high sale price of organic oil on the market (see also Palese et al. 2013). Specifically, in *Estepa*, the land spatial planning combining different types of management would allow a balance between production and environmental impacts and, thus, economic returns for farmers as well as ecological benefits. Previous studies (Rescia et al. 2017) demonstrated the importance of environmental subsidies supported by the CAP in the profitability of olive grove landscapes. However, it would be advisable for these subsidies to be more specific, that is, oriented towards organic management and focused on the delivery of ES (Guerra et al. 2016). In this way, farmers would have economic incentives to appraise the transformation of their farms and increase their profits, and at the SEL scale, society would perceive a wider spectrum of ES.

Conclusions and policy options

Our results predict that the highest rate (22%) of abandonment by farmers would occur with intensive management, with the rate being almost half of those using ecological or integrated management (11–12%), and 17% if these two types of management are combined. We estimate a loss of productive lands and benefits in the short and medium term in the more intensive crops, and we find the maximum economic return for ecological management, which could even be complemented monetarily by environmental subsidies such as those for landscape stewardship and payments for ES. These initiatives could contribute to the persistence of olive groves and their associated ES in *Estepa*, considering that scenarios partially incorporating ecological management have been shown to be more sustainable without economic subsidies. The proposed scenario, which combines different strategies of management, could allow a sound economic and environmental balance and the payment of environmental subsidies would allow the conservation of biodiversity in the unharvested abandoned areas contributing to the provision, especially, of regulating ES, harmonizing agricultural production and nature conservation, and consolidating the olive grove as a multi-services landscape. Finally, we suggest that future studies should consider the predicted effects of climate change for the development of more resilient conservation and sustainable policies for production, assuming the unmanageable and unreliable uncertainty of the predicted climate changes.

The conclusions derived from this study should not be interpreted as categorical arguments, as they constitute only the result of logically organising and making operational the available knowledge on olive grove agro-systems. The model developed should be regarded as an initial approximation of a useful tool for making deductions and predictions, and establishing a basis for a management design oriented towards olive tree sustainability in the Andalusia region. This model would be more reliable with more comprehensive studies and with improved information generated by the deeper interaction between experts and stakeholders anticipated in the near future.

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