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An assessment of soil erosion prevention by vegetation in Mediterranean Europe: Current trends of ecosystem service provision

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ABSTRACT

The concept of ecosystem services has received increased attention in recent years, and is seen as a useful construct for the development of policy relevant indicators and communication for science, policy and practice. Soil erosion is one of the main environmental problems for European Mediterranean agro-forestry systems, making soil erosion prevention a key ecosystem service to monitor and assess. Here, we present a spatially and temporally explicit assessment of the provision of soil erosion prevention by vegetation in Mediterranean Europe between 2001 and 2013, including maps of vulnerable areas. We follow a recently described conceptual framework for the mapping and assessment of regulating ecosystem services to calculate eight process-based indicators, and an ecosystem service provision profile. Results show a relative increase in the effectiveness of provision of soil erosion prevention in Mediterranean Europe between 2001 and 2013. This increase is particularly noticeable between 2009 and 2013, but it does not represent a general trend across the whole Mediterranean region. Two regional examples describe contrasting trends and illustrate the need for regional assessments and policy targets. Our results demonstrate the strength of having a coherent and complementary set of indicators for regulating services to inform policy and land management decisions.

1. Introduction

Soil erosion is one of the main environmental problems in European Mediterranean agro-forestry systems (García-Ruiz, 2010) and for the sustainability of important ecosystems (Almagro et al., 2013; Arnaez et al., 2011). Several legislative and scientific initiatives have focussed on this issue since the late 1950s and recently the Thematic Strategy for Soil Protection (TSSP) defined a coherent framework for the assessment of European soils (CEC, 2006). It pointed out the concentration of soil related risks in southern Europe and the absence of a standardized approach to obtain policy relevant indicators (Gobin et al., 2004; Panagos et al., 2014a; Van-camp et al., 2004).

The ecosystem service (ES) concept is an effective communication tool to bridge knowledge between science and policy (Maes et al., 2012; Viglizzo et al., 2012). In the case of soil erosion prevention (SEP), the TSSP recognizes the importance and knowledge gaps related to the contribution of specific ecosystems and ecosystem functions to the mitigation of soil erosion. The ES concept also supports guidelines for the development of policy relevant indicators for international monitoring systems (Reyers et al., 2013; Tallis et al., 2012) because ES indicators that are sensitive to changes in land use, calculated using standardized methods (e.g. Maes et al., 2015), provide critical sources of information for agro-forestry systems under pressure from policy, environmental or climatic drivers (Hill et al., 2008; Navarra and Tubiana, 2013).

Several studies (e.g. Martínez-Harms and Balvanera, 2012) and international initiatives (e.g. the Common International Classification of Ecosystem Services (Haines-young and Potschin, 2013)) are contributing to the development of a coherent indicator set for the mapping and assessment of ES. Under Action 5 of the European Union (EU) Biodiversity Strategy to 2020 (EC, 2011) the Working Group on Mapping and Assessment of Ecosystems and their Services (MAES) was set up to develop an assessment approach to be implemented by the EU and its Member States (Maes et al., 2013, 2014). Supported by a growing scientific literature (Costanza and

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Kubiszewski, 2012; Seppelt et al., 2011), this working group identified the need for more consistent methodological approaches to quantify and map ES and underlined the importance of finding indicators of ES provision (Müller and Burkhard, 2012) that are sensitive to measure policy impacts (Dunbar et al., 2013; Maes et al., 2012).

Vegetation regulates soil erosion and thereby provides a major contribution to Mediterranean agro-forestry system's sustainability (Iglesias et al., 2011; Olesen et al., 2011). However, the regulation of soil erosion is projected to decrease in the coming decades in the region due to overgrazing, forest fires, land abandonment, climate change, urbanization or the combination of these drivers (López-Vicente et al., 2013; Shakesby, 2011). And the intensity of these drivers has increased in the last decade (Bangash et al., 2013; García-Ruiz and Lana-Renault, 2011; Hoerling et al., 2012; Llasat et al., 2010; Otero et al., 2011). Vegetation acts as an ES provider by preventing soil erosion and therefore mitigating the impact that results from the combination of the erosive power of precipitation and the biophysical conditions of a given area. Consequently, to better represent the impacts related to these drivers it is necessary to map not only the capacity for ES provision (e.g. according to land cover type) but also the actual ES provision and the remaining soil erosion (Nelson et al., 2009).

This paper presents a spatially and temporally explicit assessment of the provision of SEP by vegetation in Mediterranean Europe between 2001 and 2013. It provides insights on past and current trends of ES provision and enables the mapping of vulnerable areas. Finally, it demonstrated the strength of having a coherent and complementary set of ecosystem service indicators to inform policy and land management decisions.

2. Methods

2.1. Study area

The Mediterranean Environmental Zones (Metzger et al., 2005) were used to define the geographic extent of the study, which was constrained to continental Europe and a few larger islands due to data availability. The study area corresponds to 1.06 Million km^2 and covers all European Mediterranean countries (Fig. 1). It encompasses three major environmental zones, i.e. Mediterranean Mountains, which experience more precipitation than elsewhere in the Mediterranean, Mediterranean North and Mediterranean South, both characterized by warm and dry summers and precipitation concentrated in the winter months (Metzger et al., 2008a,b). Within the region agriculture is generally constrained by water availability and poor soils, and grasslands, vineyards and orchards are important land cover/use features (Almeida et al., 2013; Panagos et al., 2013).

2.2. Conceptual background

The conceptual approach for mapping and assessment of regulating services used in this paper has recently been described by Guerra et al. (2014), and is summarized in Fig. 2. SEP is provided at the interface between the structural components of the agro-forestry system and its land use/cover dynamics, which help mitigate the potential impacts from soil erosion (Guerra et al., 2014, 2015). This approach combines a strong conceptual framework with the "avoided change" principle, characterizing regulating ES provision as the degradation that does not happen due to the contribution of the regulating ES provider (i.e. the vegetation cover) (Layke et al., 2012).

To assess SEP following this framework it is necessary to first identify the *structural impact* (Υ) related to soil erosion, i.e. the erosion that would occur when vegetation is absent and therefore no ES is provided (Fig. 2a). It determines the potential soil erosion in a given place and time and is related to rainfall erosivity (i.e. the erosive potential of rainfall), soil erodibility (as a characteristic of the soil type) and local topography (Panagos et al., 2011; Ribeiro et al., 2004). Although external drivers can have an effect on these variables, they are less prone to be changed directly by human action.

The *actual ES provision* (*Es*) is a fraction of the total potential soil erosion (i.e. *structural impact*: Υ), and it is determined by the *capacity for ES provision* (e_s) in a given place and time. We can then define the latter as a key component to quantify the fraction of the *structural impact* that is mitigated (Fig. 2b) and to determine the remaining soil erosion (i.e. the *ES mitigated impact* (β_e)). This *capacity for ES provision* is influenced by both internal drivers (including land management options, forest fires, and urban sprawl) and external drivers (including agricultural policy measures, spatial planning, and climate change). A detailed description of the methodological and conceptual frameworks is given in Guerra et al. (2014).

2.3. Indicators of ecosystem service provision

To understand the relation between drivers and the provision of ES, it is essential to translate the dynamics of the agro-forestry systems into a set of process related indicators that express system responses (Müller and Burkhard, 2012; Guerra et al., 2015). We propose a set of eight indicators that describe the different processes that contribute to SEP (Table 1), including indicators describing the state and dynamics of the *structural impact* (Υ), the *ES mitigated impact* (β_e), the *actual ES provision* (*Es*) and the *capacity for ES provision* (e_s). Together, these eight indicators are sensitive to changes in the climatic profile of each region, soil types, topography, management options and environmental drivers. Although all indicators have been produced at a 250 m resolution, these were finally aggregated by summation to a 5 km grid (25 km^2) resolution to better communicate changes and trends in ES provision and to avoid false precision related with the different data quality of the input datasets. In the case of the *capacity for ES provision* the average was used as, considering the adimensional character of this indicator, the sum does not provide any relevant interpretation value.

2.4. Datasets and methodological application

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), a commonly used empirical model for the determination of potential soil losses (Amore et al., 2004; Fistikoglu and Harmancioglu, 2002), was used to calculate SEP between 2001 and 2013. Soil erosion is represented by a set of critical factors given by (Panagos et al., 2011):

$$A = R \times LS \times K \times C \times P$$

where A (ton ha^{-1}) represents the amount of soil loss, R (MJ mm ha^{-1} h^{-1}) the rainfall erosivity, LS (dimensionless) the topographic factor, K (t ha h ha^{-1} MJ^{-1} mm^{-1}) the soil erodibility, C (dimensionless) the vegetation cover factor and P (dimensionless) the conservation practices factor.

For the ES assessment, the *structural impact* (Υ) was calculated using the expression $\Upsilon = R \times LS \times K$ (Prasuhn et al., 2013), and the gradient of *ES mitigated impact* was determined by $\beta_e = \Upsilon \times \alpha$ (where $\alpha = C$ and $e_s = 1 - \alpha$). Technical infrastructure that could reduce impacts locally was not consider given the spatial scale of the study. Following these two expressions the *actual ES provision* (E_s) can be calculated by $E_s = \Upsilon - \beta_e$. Although no absolute measure of soil erosion is obtained, this mathematical formulation will

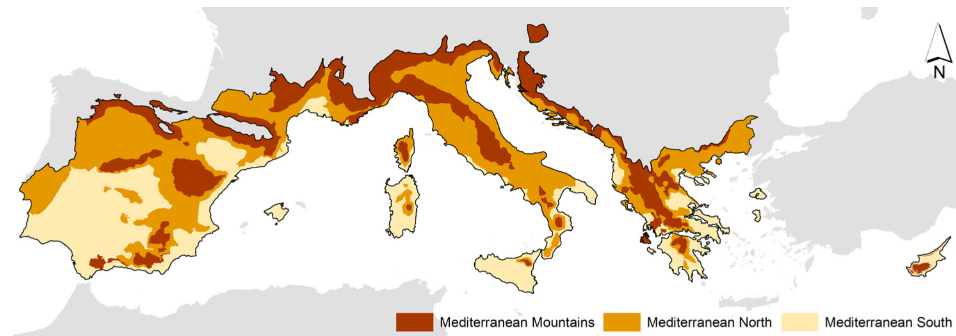

Fig. 1. Geographic scope of the study area according to the European Environmental Stratification (Metzger et al., 2005).

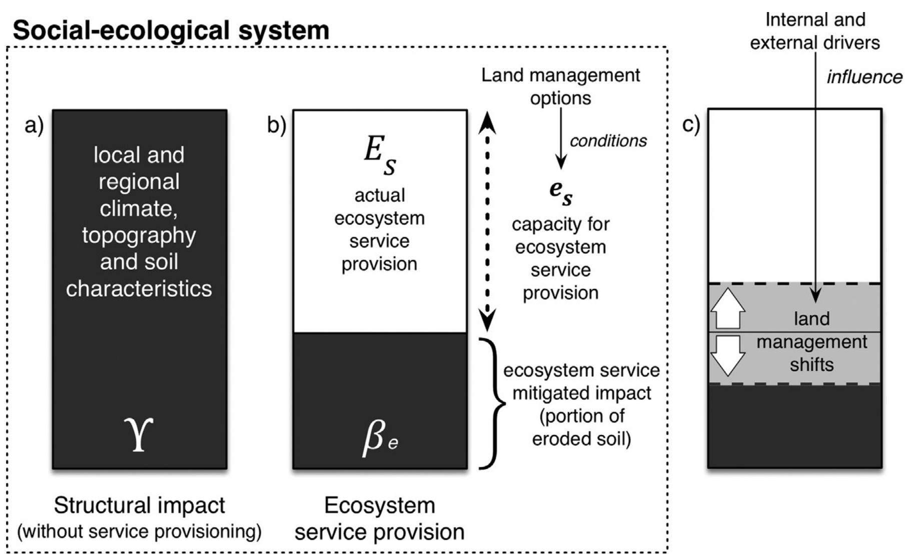

Fig. 2. Conceptual framework for assessing the provision of regulating services (adapted from Guerra et al., 2015), where (a) presents the *structural impact* (Υ) (i.e. the total soil erosion impact in the absence of SEP); (b) distinguishes the *actual ES provision* (*Es*) as an avoided portion of the *structural impact* (measured in tons of soil not eroded) and determined by the *capacity for ES provision* (e_s) (i.e. the fraction of the *structural impact* that is mitigated by the ES, corresponding to an adimensional gradient ranging from 0 to 1), and the remaining *ES mitigated impact* (β_e) (i.e. the remaining soil erosion that is not regulated by SEP); and (c) considers the variations in the *actual ES provision* resulting from changes in land management that occur at the local level although influenced by internal and external drivers.

Table 1
List of calculated indicators to describe the state and dynamics of ES provision (all indicators are provided at a 5 km grid resolution).

Indicator	Description	Units
Structural impact	Total soil erosion impact when no ecosystem service is provided	Tons of soil per pixel area
Ecosystem service mitigated impact	Total of the remaining soil erosion after the ecosystem service provision	Tons of soil per pixel area
Actual ecosystem service provision	Total of the actual ecosystem service provision corresponds to the total amount of ecosystem service provided, measured in ecosystem service providing units (tons of soil not eroded). It varies from season to season and year-to-year depending on the variation of the structural impact	Tons of soil per pixel area
Ecosystem service provision capacity	Average fraction of the structural impact that is mitigated by the ecosystem service, it corresponds to an adimensional gradient from 0 to 1	–
Variation in structural impact	% Variation in the total amount of structural impact considering the previous reference date	%
Rate of effective ecosystem service provision	% Variation in the total amount of actual ecosystem service provision corrected by the structural impact fluctuations for a given region using the following expression: $100\times\left(\left[\frac{Es_{t+1}}{Es_t}-1\right]-\left[\frac{\Upsilon_{t+1}}{\Upsilon_t}-1\right]\right)$, where *Es* is the total actual ecosystem service provision, Υ is the total structural impact, and *t* corresponds to the temporal frame.	%
Variation in ecosystem service provision capacity	% Variation in the total amount of ecosystem service provision capacity considering the previous reference date	%
Variation in ecosystem mitigated impact	% Variation in the total amount of ecosystem service mitigated impact considering the previous reference date	%

generate a spatially explicit gradient of the potential soil loss and the related gradient of ecosystem service provided by vegetation cover (Guerra et al., 2014). Artificial surfaces were excluded from the evaluation and all parameters (after estimation) were directly resampled to a 250 m resolution using an average filter.

2.4.1. Rainfall erosivity

The rainfall erosivity was estimated using the MedREM model proposed by Diodato and Bellocchi (2010) for Mediterranean conditions for the years of 2001, 2005, 2009 and 2013. This model was originally calibrated and validated using 66 meteorological stations distributed throughout the Mediterranean basin with multi-year data of rainfall erosivity (Diodato and Bellocchi, 2010). It considers the variability in rainfall distribution and intensity and also the longitudinal differences within the Mediterranean basin. Rainfall erosivity was calculated between the months of August and November, corresponding to the most critical period for soil erosion in Mediterranean conditions (Luis et al., 2010). Daily rainfall observations, available through the European Climate Assessment and Dataset (ECA&D; http://eca.knmi.nl/; Haylock et al., 2008), were divided into four partially overlapping temporal time slices ([1991–2001]; [1995–2005]; [1999–2009]; [2003–2013]). For each time slice, the rainfall erosivity factor was calculated using the following expression (adapted from Diodato and Bellocchi, 2010):

$$R_m = b_0 \times p_m \times \sqrt{d_m} \times (a + b_1 \times L)$$

where R_m (MJ mm ha^{-1} h^{-1} month^{-1}) corresponds to the monthly erosivity factor for the month m, b_0 (MJ ha^{-1} h^{-1}) is a constant equal to 0.117, b_1 (d$^{0.5}$ mm$^{-0.50-1}$) is a constant equal to 2, a (d$^{0.5}$ mm$^{-0.50}$) is a constant equal to −0.015, L (°) corresponds to the site longitude, P_m (mm) to the total amount of precipitation in a given month m, and d_m (mm d^{-1}) to the monthly maximum daily precipitation for month m averaged over a multi-year period (in this case a 10 years period was selected).

2.4.2. Soil erodibility

For the soil erodibility parameter we used the high resolution (500 m resolution) European soil erodibility map (Panagos et al., 2014b) calculated from data collected in the Land Use/Cover Area frame Survey (LUCAS) soil survey for 2009. This was calculated based on the equation proposed by Wischmeier and Smith (1978) and Renard et al. (1997) (Panagos et al., 2014b):

$$K = \left[(2.1 \times 10^{-4} M^{1.14}(12 - a) + 3.25(s - 2) + 2.5(p - 3))/100\right] \times 0.1317$$

where K corresponds to the soil erodibility factor, a is the percentage of organic matter, b the soil structure parameter, c the profile permeability class, and $M = (\%_{\text{silt}} + \%_{\text{ver fine sand}}) \times (100 - \%_{\text{sand}})$.

2.4.3. Topography

For the topographic factor the SRTM shuttle DEM (90 m) was used following the expression proposed by Moore and Burch (1986):

$$LS = \left(\frac{a \times p}{22.13}\right)^{0.4} \times \left(\frac{\sin(d)}{0.0896}\right)^{1.3}$$

where LS represents the topographic factor, a refers to the flow accumulation model obtained from the topographic dataset, p to the pixel size (90 m), and d to the slope model in degrees.

2.4.4. Vegetation cover

To estimate the capacity for ecosystem service provision it is necessary to obtain an approximation of the vegetation cover parameter. This parameter was estimated for each time slice using the relation between the Normalized Difference Vegetation Index (NDVI; calculated from MODIS 16 days NDVI composites with a 250 m pixel resolution) and the USLE C Factor proposed by Van der Knijff et al. (1999, 2000) (Prasannakumar et al., 2012):

$$C = \exp\left[-a \times \frac{NDVI}{(b - NDVI)}\right]$$

where $a = 2$ and $b = 1$.

2.4.5. Integrated analysis and vulnerability assessment

The spatial distribution and temporal trends of the indicators (see Table 1) were analyzed and mapped, and an overall ES provision profile was calculated for the entire study area. This was done using spatial statistics to obtain a total sum value (or an average value in the case of the *capacity for ES provision*) for the entire study area, and made it possible to isolate vulnerability areas and to pinpoint the periods with higher impact on SEP.

The vulnerability areas were identified by superimposing the variation of the *capacity for ES provision* (positive or negative), with the variation of the *ES mitigated impact* (positive or negative), both calculated between 2001 and 2013. A breakdown of the total land surface area covered by different combinations of these two variables reveals four groups related to each of the four quadrants (Fig. 5). The first group (1Q) represent areas that, despite their increase in the *capacity for ES provision*, reveal an increase of *ES mitigated impact*, i.e. despite the increase of vegetation capacity to halt soil erosion, there was an increase in the remaining soil erosion after the ES provision. The second (2Q) consisted of areas with a decrease of the *capacity for ES provision* and an increase of the *ES mitigated impact*, i.e. this group reflects the expected trend that a decrease in vegetation capacity to halt soil erosion resulted in more soil erosion. In the third group (3Q) are combined areas with a decrease of both the *capacity for ES provision* and the *ES mitigated impact*, i.e. reflecting a reduction in the efficiency of the ES to halt soil erosion, and finally the fourth group (4Q) included areas with an increase of capacity related to a decrease of the *ES mitigated impact*. This assessment thus identifies three types of vulnerable areas that require policy action (i.e. 1Q, 2Q, and 3Q).

Following this analysis, two smaller case-studies with contrasting regional ES provision profiles are described. Their specific ES provision profiles were constructed based on the description of the main indicators following the same methodological approach as for the overall ES provision profile described for the entire study area.

3. Results

3.1. States and trends of the structural impact

The *structural impact* (Υ) followed the rainfall dynamics during the same period: decreasing between 2001 and 2009 but increasing toward 2013. Overall, a decrease of 7.86% was observed between 2001 and 2013. Using 2013 as a reference year, the distribution of the *structural impact* (Fig. 3) showed relatively high values in the north of Italy, south of France, the East coast of the Adriatic Sea and the western and southern areas of the Iberian Peninsula. This spatial distribution remained throughout the period of the analysis with the exception of 2009, when the distribution was less pronounced. Between 2001 and 2013 the areas that experienced an increasing *structural impact* over the four months in analysis were located in the south of Italy and in the south of the Iberian Peninsula (Fig. 3). The results also showed that this increase is mainly related to an increase and higher variability of the *structural impact* (related to an increase in precipitation) in October following a dip in September.

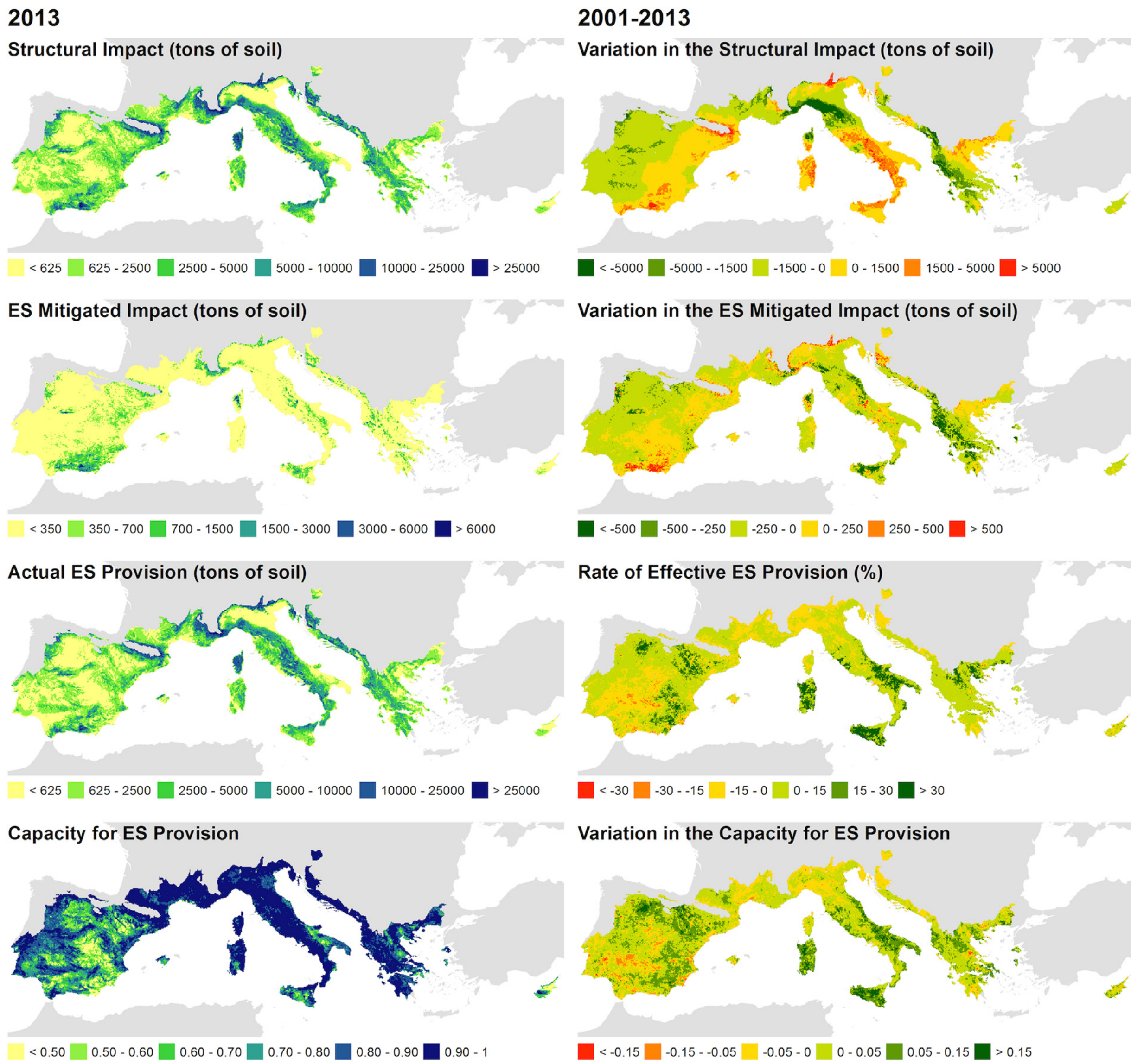

Fig. 3. Spatial distribution of the different indicators calculated to illustrate the spatial and temporal distribution of SEP in Mediterranean Europe (all indicators were computed based in a 5 km grid).

3.2. States and trends of the ES mitigated impact

The *ES mitigated impact* (β_e) presented a different trend from the *structural impact* with an increase between 2001 and 2005 followed by a relatively constant decrease in its values until 2013. For 2013 (Fig. 3) it showed a concentration of high values mainly in the Southeast of the Iberian Peninsula, and in particular areas of the North of Italy and South of France. Together with some areas in the East of the Iberian Peninsula, South of Italy, and East of Greece, these areas also corresponded to the regions where this indicator has increased between 2001 and 2013. This trend implies a degradation of the conditions present in a given place as the total amount of soil loss (after the provision of SEP) increased. Despite of these degradation areas, the overall result for the entire region showed a decrease of 15.09% of *ES mitigated impact* between 2001 and 2013. This decrease was mainly located in Greece and in large portions of Italy, Spain and Portugal.

3.3. States and trends of ES provision

As expected, the *actual ES provision* (*Es*) showed the same spatial and temporal pattern as the *structural impact* (Fig. 3). By contrast, the *capacity for ES provision* (e_s) revealed two very different patterns. The first pattern included the Iberian Peninsula and some areas in Southern Italy and in Eastern Greece, which were characterized by lower values and a more differentiated distribution of this indicator. The spatial location of these low values was similar to the spatial distribution of high values of *structural impact*, particularly in the South of the Iberian Peninsula and in the South coast of Italy (see Annex 1). The second pattern concerned areas that showed more homogeneous distribution of higher values of the *capacity for ES provision*. Examples of these areas are the South of France, the East coast of the Adriatic Sea and the North of Italy. Despite this variable distribution, considering the entire region the overall values of the *capacity for ES provision* increased slightly between 2001 and 2013, from 0.815 to 0.844 (Fig. 4). This increase originated mainly from the South and East coast of Italy and from large areas in the North of Iberian Peninsula, while in the South of the Iberian Peninsula the *capacity for ES provision* decreased between 2001 and 2013. This overall increase is the result of a constant positive trend between 2001 and 2013 that is more substantial between 2009 and 2013 (Fig. 4). Regarding these areas in the South of the Iberian Peninsula, and using the monthly

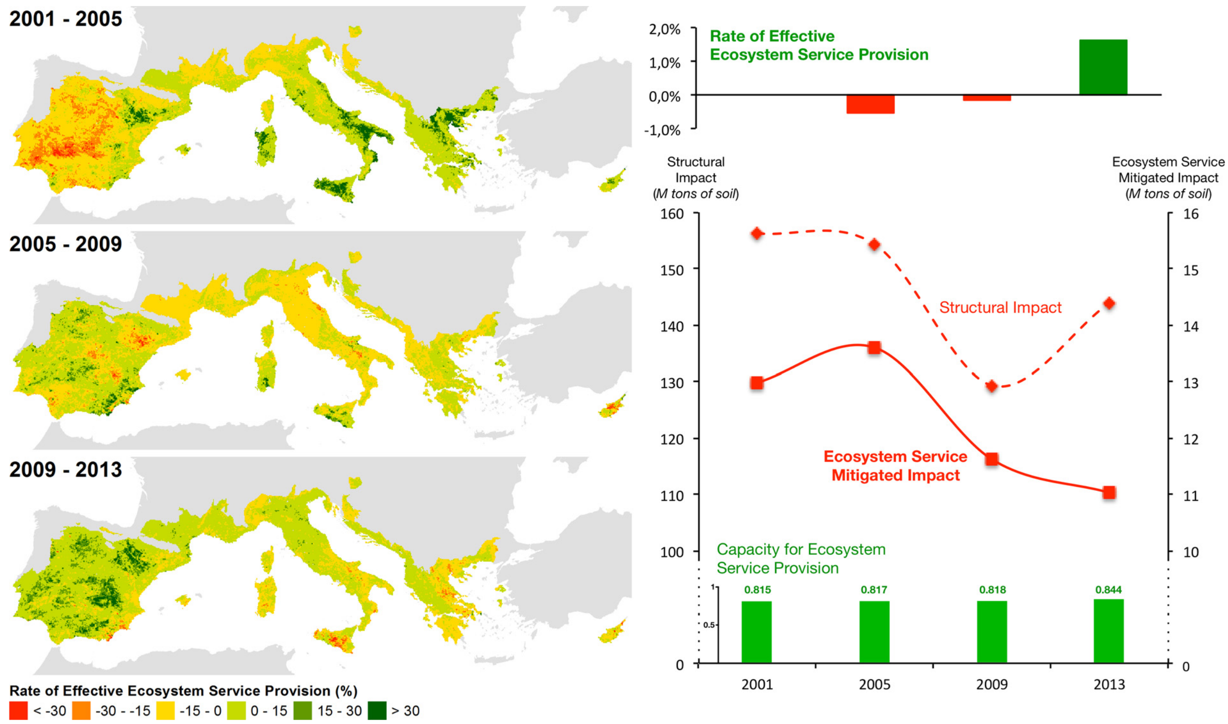

Fig. 4. Spatial distribution of the *rate of effective ES provision* for the different periods considered (on the left) and the overall ES provision profile representing the different SEP indicators aggregated for the entire study area (on the right).

variation of the *capacity for ES provision*, we infer that this decreasing trend was related mainly to a decrease of provisioning capacity in October, particularly between 2001 and 2005. These spatial and temporal decrease patterns of the *capacity for ES provision* were in line with the increase of *structural impact* in the region.

A more detailed analysis of the *rate of effective ES provision* (Fig. 4) showed substantial dissimilarities between the different regions that were even more pronounced over the entire period (2001–2013) (see Fig. 5 for an example). While in the first period (2001–2005) the Iberian Peninsula showed substantial losses (*rate of effective ES provision* equal to −5.21%), in the following periods these losses were located more toward the North of Italy and the South of France (2005–2009) and to the South of Italy and Greece (2009–2013). Overall, although not statistically significant ($p = 0.05$), the entire study region presented a positive trend in terms of the effectiveness of service provision (0.66%), particularly in the period between 2009 and 2013 where the *rate of effective ES provision* increased by 1.62% (Fig. 4).

The vulnerability analysis revealed that 43.5% of the total area is related to one of the three groups of vulnerable areas (i.e. 1Q, 2Q and 3Q) (Fig. 5a). The second (2Q corresponding to 16.5% of the total area) and the fourth group (4Q corresponding to 56.5% of the total area) demonstrated the expected inverse relation between the *capacity for ES provision* and the *ES mitigated impact*. Put differently, the increased capacity to prevent soil erosion is generally positively correlated to a decrease in soil erosion. In contrast, the other two groups included areas where despite an increase of capacity there is still an increase of impact (1Q corresponding to 18.8% of the total area), as well as areas where a decrease of capacity is followed by a decrease of the *ES mitigated impact* (3Q corresponding to 8.2% of the total area). Therefore to interpret trends of SEP provision to formulate effective mitigation measures these two different indicators need to be considered (i.e. the *capacity for ES provision* and the *ES mitigated impact*). Combined, these two indicators give a clear picture of the underlying questions that rise in each area. Fig. 5 suggests that in 64.7% of the total area the *ES mitigated impact* decreased, mainly due to an increase of the *capacity for ES provision*. In contrast, from the 35.3% of areas with an increase of the *ES mitigated impact*, 53.3% also showed an increase of the *capacity for ES provision*.

The two selected case-study regions (Fig. 5b and c) illustrate two very different trends. R1, the NUTS 3 Ciudad Real in Spain (Fig. 5b), presents an overall (2001–2013) negative trend of the *rate of effective ES provision* (−4.73%). This happens despite the slight increase in the *capacity for ES provision* (0.84%) in the same period and is related to the substantial increase (118.14%) in the *ES mitigated impact* in the first period (2001–2005), which resulted from a decrease of 15.08% in the *rate of effective ES provision* for the same period. Despite the recent (2005–2013) improvements in the *rate of effective ES provision*, the regional SEP dynamics resulted in an increase of 43.98% of the *ES mitigated impact* between 2001 and 2013. In contrast, R2, the NUTS 3 Trikala in Greece (Fig. 5c), presents an overall (2001–2013) negative trend of the *rate of effective ES provision* (4.71%) accompanied by a decrease of 58.04% of the *ES mitigated impact* in the same period. Although this region presents a positive development in terms of SEP provision, the general trend of the *rate of effective ES provision* (2001–2013) shows a systematic decrease in the period of analysis, despite the increase of 5.19% in the *capacity for ES provision*.

4. Discussion

4.1. Methodological potential and limitations

The analysis of the spatial and temporal distribution of SEP used a diverse set of process indicators that encompass the impacts related to the dynamics of soil erosion and to the service provision generated by vegetation. Compared to other methodological approaches that usually base their assessments on a single indicator (e.g. Koschke et al., 2012; Helfenstein and Kienast, 2014; Frélichová et al., 2014), our approach provides more insight and more easily identifies the relations between the underlying landscape

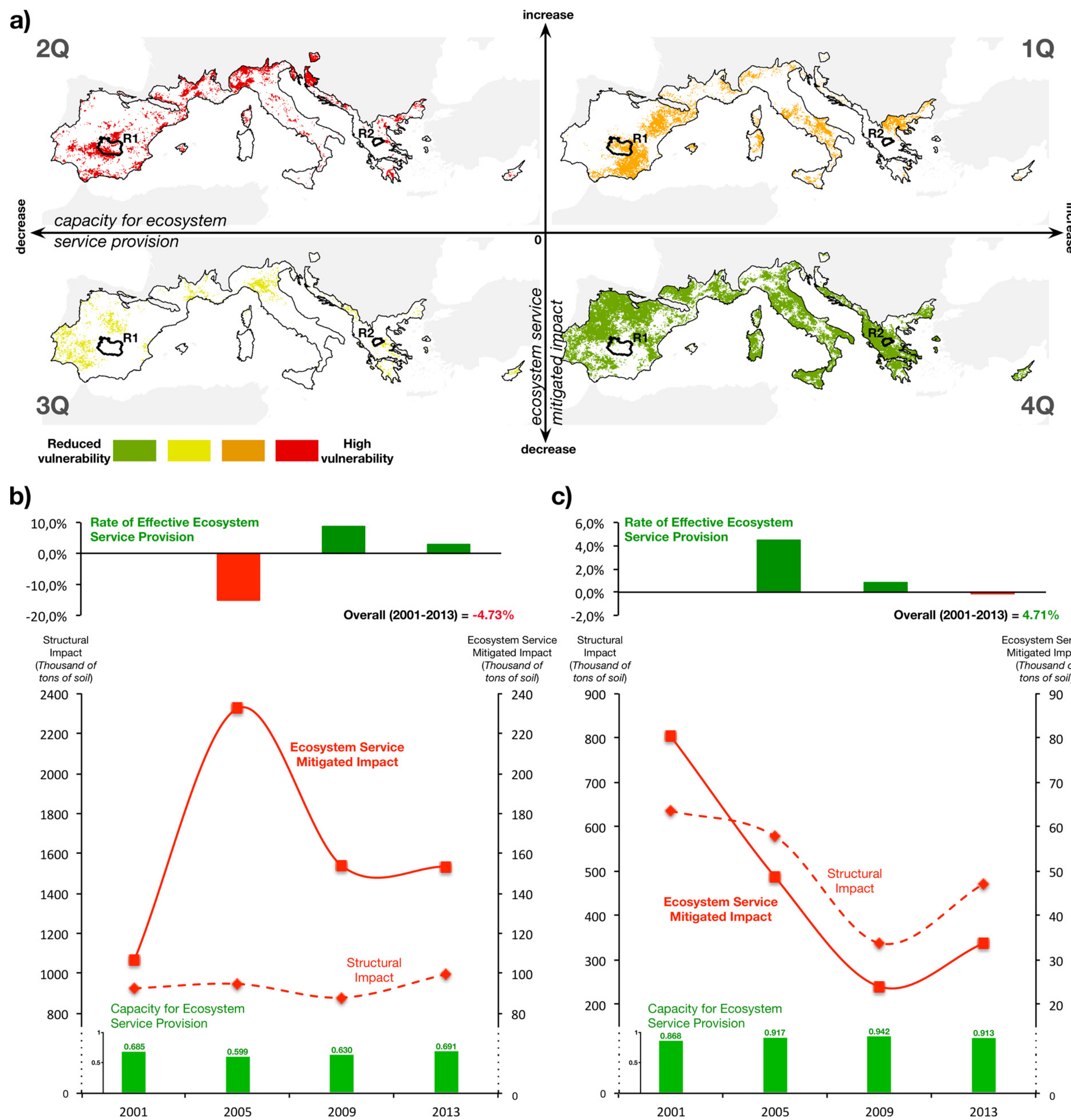

Fig. 5. Representation of: (a) the spatial distribution of the grid cells discriminated by the variation (2001–2013) of the *capacity for ES provision* (horizontal axis) and the variation (2001–2013) to the *ES mitigated impact* (vertical axis); (b) the regional ES provision profile for R1, corresponding to the NUTS 3 Ciudad Real (Spain); and (c) the regional ES provision profile for R2, corresponding to the NUTS 3 Trikala (Greece).

processes and their consequences in terms of service provision and of the remaining impacts. Also, although the *actual ES provision* can be used as an indicator for valuation purposes, it is not a good "stand alone" indicator for trend analysis as it is dependent on the spatial distribution, magnitude and temporal trend of the *structural impact* (Guerra et al., 2015).

Our results show that the *rate of effective ES provision* can be a more insightful indicator as it provides a better grasp of the local/regional ES provision performance. This indicator corresponds to the percentual variation of the early time slice (e.g. 2001) in comparison to the following (e.g. 2005). This means that if a particular area lost a considerable amount of ES provision in a given period, it is probable that in the next period it registers a gain (e.g. from the recovery from a previous forest fire). Although this does not mean that the net provision of ES was positive considering the entire period (2001–2013). This was illustrated in the South of the Iberian Peninsula where in the first period (2001–2005) there was a substantial loss of the *rate of effective ES provision* accompanied by relative gains in the following periods, although, in the same area, there was a cumulative increase of the *ES mitigated impact*. In this case this dynamic can also be explained by the high variation in the *capacity for ES provision* registered in the region (Annex 2).

SEP alone cannot be used to determine the effectiveness of ES provision in a given region (Dunbar et al., 2013; Fitter et al., 2010). It is also important to consider the interactions and eventual trade-offs between services in more strategic assessment of the net ES provision in a given region to better define local environmental targets.

4.2. SEP provision and vulnerability assessment

Our results illustrate the value of having a comprehensive and complementary group of process-based ES indicators. They show an overall, non-significant, increase in SEP in the region. A worrying trend becomes apparent when assessing areas that showed a decrease of the *capacity for ES provision* and an increase of the *ES mitigated impact* (Fig. 5 2Q). These areas (corresponding to 16.5% of the total study area) point to the eventual insufficiency, ineffectiveness or non-existence of soil protection measures and reflect very important regional differences. While in Italy, the Northeast coast of the Baltic Sea and the South of France this dynamic is related to a predominance of forest areas, in the Iberian Peninsula and in Greece it is related to a predominance of agricultural areas. This vulnerability analysis also shows that, between 2001 and 2013, 25% of areas with an increase of the *capacity for ES provision* were subject to a further increase of soil loss. These results are related to the 18.8% of areas with an increase of both the *ES mitigated impact* and the *capacity for ES provision* (Fig. 5 1Q), revealing a situation where the presence of protective vegetation cover did not result in an enhanced soil protection.

The two smaller case-studies (Fig. 5b and c) illustrate the power of creating a regional ES provision profile for assessing the efficiency of SEP. In R1 we observe that even with an overall increase of 0.88% in the *capacity for ES provision*, the region had an increase of 43.98% of the *ES mitigated impact* following a decrease of 4.73% in the *rate of effective ES provision*. Although there is an improvement in SEP provision in recent years (2005–2013), this exposes the insufficiency of current regional initiatives to halt soil erosion by promoting SEP. By contrast, R2 shows a completely different pattern with constant gains of efficiency, even when (between 2009 and 2013) there is a decrease of 3.07% in the *capacity for ES provision* that is reflected in a slight decrease of 0.08% on the *rate of effective ES provision*. Both examples demonstrate the possibility to define regional targets that can steer regional conservation and economic development policies that aim to minimize these impacts and their effects on human wellbeing.

4.3. Policy and research implications

Declines in regulating services provision like SEP can result in declines in ecosystem resilience (Bennett et al., 2009), and affect the provision of other ES. Our results show that, in total, 43.5% of the entire study area presented some type of vulnerability regarding the mitigation of soil erosion. If this information would be available in national and international monitoring systems, policy and management decisions could be better informed and action could be taken timely.

The insight provided by the combination of indicators suggests that current policies and land management fail to safeguard SEP to halt soil erosion. One possible explanation could be that most of the policies that land managers follow correspond to generic top-down sectorial approaches. The spatial patterns and indicator values found here indicate that further disaggregation, consideration of context, and place-based or regional targets could improve SEP in Mediterranean Europe and prevent undesired ES provision trajectories.

Finally, in future research, the relative positive trends found in this paper should be contextualized and regionally assessed in relation to regional social, ecological and economic. This means that further research should identify whether the observed positive trends correspond to an increase of management efficiency and/or policy implementation or if they are related to land abandonment processes that eventually resulted in an increase in the capacity for SEP.

5. Conclusions

This paper produced a spatially and temporally explicit assessment of the provision of SEP in Mediterranean Europe in the last decade (2001–2013). We found that in general the provision of this service is increasing in Mediterranean Europe, particularly between 2009 and 2013. Despite these positive results 43.5% of the region is vulnerable and in need of focused attention to identify causes and implement effective mitigation measures. The results suggest that current policy and land management actions are not safeguarding the provision of SEP. This emphasises the need to evaluate and assess regulating ES considering a bundle of process based ES indicators. Particularly for SEP this would provide a clear representation of the different dynamics associated to the provision of the service. This study suggests the need for more adaptive policy design that can cope with local trends of ES provision and the definition of regional ES provision targets to mitigate regionally relevant impacts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2015.06.043

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