ASSESSING SOIL QUALITY AND CLIMATE REGULATION IN RURAL PORTUGAL: INSIGHTS FOR DECISION MAKING

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Abstract

The 'CULTIVAR', a research and innovation project for the sustainable development of agri-food sectors implemented in the Portuguese Beira Interior region, aimed to address agroecosystems' challenges in low-density areas through a territorial development strategy. It included assessing and mapping key ecosystem services (ES), namely provisioning services (cultivated terrestrial plants and reared animals for nutrition) and regulating and maintenance ES (soil quality and climate regulation). The study area involved seven municipalities in Central East Portugal, where the land is mainly forest, followed by productive land uses (farmland, grassland and agroforestry). For provisioning services, average productivity data from each parish was assigned to those productive land uses. Considering the LUCAS database, the carbon-to-nitrogen ratio was the proxy indicator for soil quality. For climate regulation, the assessment targeted aboveground carbon sequestration, which considered the reference values of the Portuguese Forest Inventory assigned to the Conjunctural Land Cover Map, and belowground carbon storage, considering the organic matter values (%) from the LUCAS and WoSIS database. The assessed ES were spatially assigned to the EEA reference grid for Europe (1km) (N = 5903 grid). A hot spot analysis helped identify synergies and mismatches between the four ES. Concerning provisioning services, 11% and 15% of the study area were agriculture and livestock production hot spots. For soil quality and carbon sequestration, 20% and 18 % of the area corresponded to cold spots, and 12% and 19% to hot spots, respectively. Carbon stock was negatively correlated with the other 3 ES (especially soil quality and livestock), while soil quality is positively correlated with both provisioning services (especially livestock production). This information gave insights into the ES's trade-offs, fundamental for drawing up management recommendations.

Keywords: *provisioning services, regulating services, carbon stock, agroecosystems, Portugal*

1. INTRODUCTION

The low-density areas in the Iberian Peninsula face multiple challenges linked to agricultural abandonment or intensification. Both processes impact ecosystem services (ES) delivery, essential for environmental sustainability and human well-being [1].

Agricultural abandonment has negative and positive impacts on ES, including reducing the supply of provisioning services or the loss of cultural landscapes. However, it might also enhance regulating services such as biodiversity support, water quality, carbon storage or soil quality [2, 3, 4, 5].

On the other hand, agricultural intensification, driven by the increasing demand for agricultural goods, often results in negative impacts on biodiversity and regulating services, such as water and climate regulation or soil quality, that are crucial to the resilience and health of agroecosystem [6, 7, 4]). In Europe, the shift from traditional low-intensity management to more intensive practices has resulted in mismatches affecting ES supply [8]. Those intensively managed agrosystems often lack crucial regulating services, making them more prone to the impacts of climate change. This vulnerability compromises the provision of services, ultimately posing risks to food security. Thus, it is crucial to define adaptation strategies that enhance resilience and maintain ES flows [9].

Understanding the synergies and mismatches between provisioning and regulating services in agroecosystems is necessary for optimising trade-offs and ensuring sustainable agricultural practices [10].

This work aimed to understand the existing synergies and mismatches between ES food production (agriculture and extensive cattle production) and ES regulating and maintenance (soil quality and climate regulation), to support decision-making, considering the best trade-off between those ES.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in eastern-central Portugal, covering seven municipalities [11] in the Beira Interior region (Sabugal, Penamacor, Covilhã, Belmonte, Fundão, Idanha-a-Nova and Castelo Branco) (Figure 1a). Altitude ranges from 104 to 1993 meters (Figure 1b). It includes part of a mountain range known as 'The Iberian Central System', which includes, on the East side of the study area and includes the 'Malcata', 'Opa' and 'Penha Garcia' mountains, and in the West side, the 'Gardunha' and part of 'Estrela', 'Lousã' and 'Açor' mountains. This Central System divides the 'Central Meseta Iberica', being in the north a plateau marked by a highland landscape, with the main watercourse belonging to the Douro watershed, and in the south a peneplain surface where the watercourses flow into the Tagus river basin. The southern region also includes a geomorphological unit known as 'Cova da Beira', a tectonic depression surrounded by the mountain range and a less productive region surrounding the Tagus River (Figure 1c).

The study area is sparsely populated, due to the rural abandonment of the last decades [12], being predominantly a rural matrix dominated by forestry (43%), followed by farmland (22%), shrublands (14 %), grassland (11%) and agroforestry (6.5%) [13]. The remaining 3.5% is occupied by urban areas, sparsely vegetated areas, and water. The landscape units are very different (Figure 1d). Cova da Beira is specialised in agricultural areas (48%), followed by forests (27%). East mountains are occupied mainly by forests (69%), the highest area of this class, followed by shrublands (13%). The northern plateau has a more diverse landscape, where the main classes are forest (35%), scrubland (22%), agriculture (21%), and pastures (10%). In the Southern plain, the Agricultural and Forest classes have the same land use dominance (32%), and the Pasture class occupies 18%. In the Tagus region, forest leads (43%), followed by the agroforestry class, which has the highest expression of the whole area and reaches 21%, and pastures account for 18%. Western mountain's main class is forest (60%), and focal species are Eucalyptus and maritime pine, scrubland (21%), and agricultural areas (13%).

There are two main productive models in the study area. One is the agricultural background of the region, based on extensive production (crops and livestock) that are rainfed or traditional irrigated crops using the available water resources. The other occurs in the two regions ('Cova da Beira' and 'Idanha-a-Nova peneplain') with irrigation infrastructures where agricultural practices have been intensified. This dynamic has gained spatial expression in this region over the last two decades (Figure 1e).

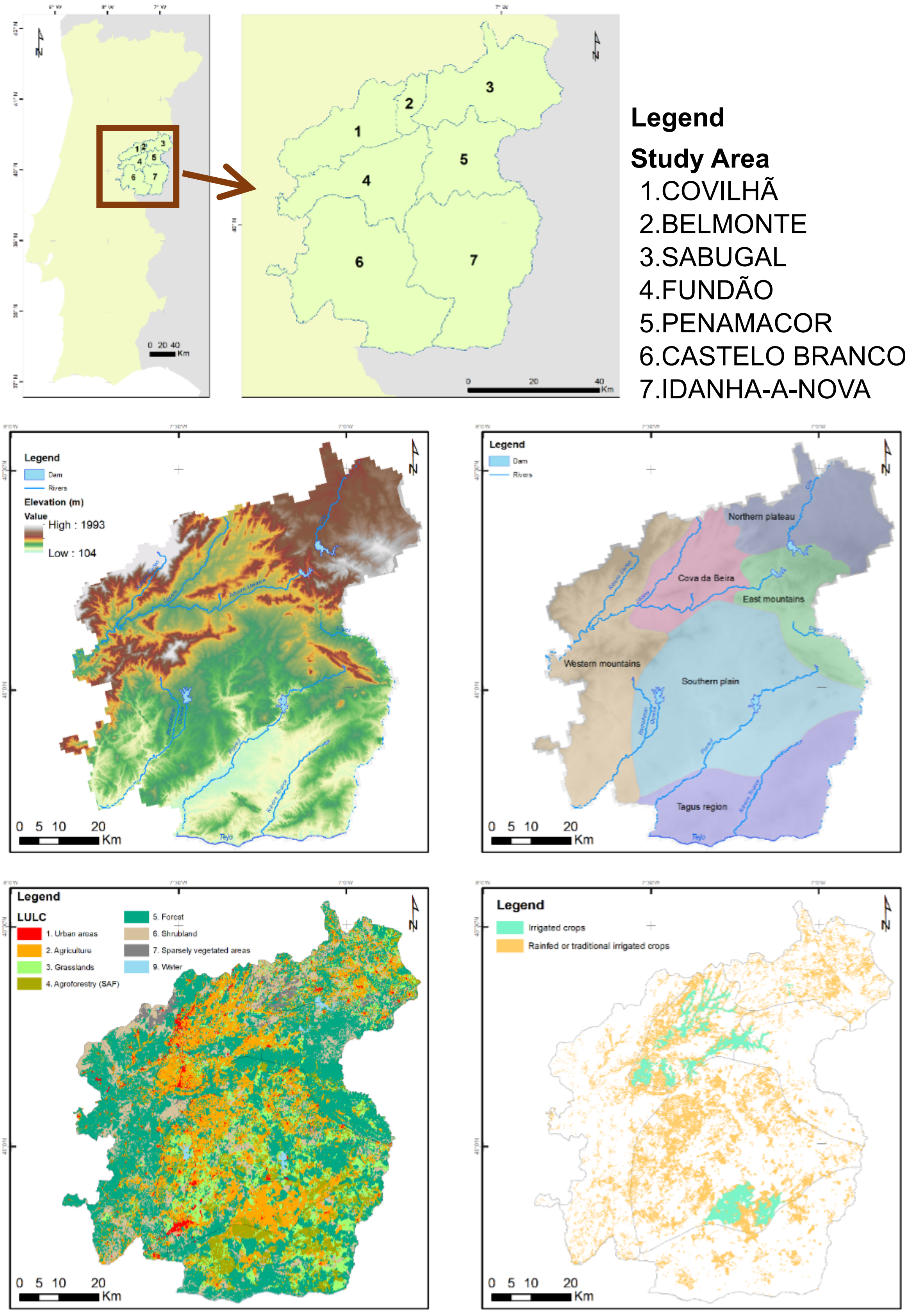

Figure 1. a) Study area: the seven municipalities in central Portugal; b) Elevation; c) Main landscape units in the study area; d) Land Uses Land Cover (LULC) from the study area; e) Irrigated and rain-fed agricultural areas.

2.2. Methods

2.2.1 Ecosystem Services assessment and mapping

Four ES were evaluated and mapped: two provisioning ES (plant production and animal production for nutrition) and two regulating and maintenance ES (soil quality and climate regulation), through the assessment of proxy indicators (Figure 2).

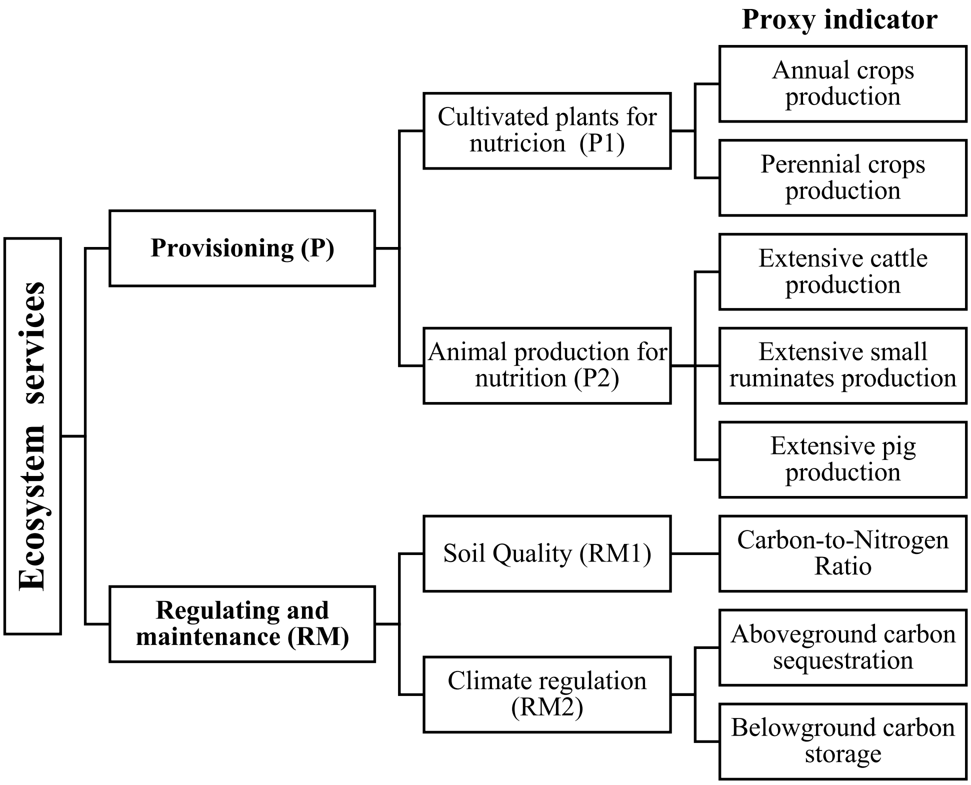

Figure 2. The proxy indicators used to assess the selected ecosystem services

Cultivated plants for nutrition (P1), mainly linked to agriculture (annual and perennial crops), and reared animals for nutrition (P2), concerning livestock extensive production (cattle, small ruminants, and pig production) were assessed based on the national database which provided average productivity data from 2009 to 2019 for each parish [14]. This data was then categorised according to the productive land use classes defined in the Portuguese land use and land cover (LULC) database [13]

Permanent and annual crop productivity (P1) was assigned considering the effective area occupied by the corresponding land use in each parish. For livestock productivity (P2), we analysed the number of animals (cattle, goats, sheep, and pigs) per parish [14]. That data was associated with the most typical land use they occupy, based on expert opinion (e.g., cattle mainly feed in agroforestry and grassland areas). Then, following the Portuguese guidelines [15], the number of animals was standardised into 'Normal Head' (NH). This unit represents the equivalence between the different livestock types regarding the total number of units considered in management (Appendix A).

For soil quality (RM1), the C/N ratio obtained from the LUCAS [16] and WoSIS [17] databases was used as a proxy indicator. All in-land Iberia Peninsula sample points (N=642) were used to characterise soil quality for each LULC class. The C/N ratio is a critical indicator of soil quality and fertility, reflecting the balance of carbon and nitrogen being used to assess soil health and its ecological functions. This ratio influences nitrogen immobilisation and mineralisation during organic matter decomposition.

A lower C/N ratio generally indicates higher nitrogen mineralisation rates, which is crucial for plant growth and soil fertility [18, 19, 20].

Regarding climate regulation (RM2), the two proxy indicators were used: 1. The aboveground carbon sequestration refers to the carbon stored in plant biomass. Three carbon pools were considered for forest classes: above and belowground biomass and litter. This proxy was estimated for all land uses classes and calculated based on the Portuguese 6th Forest Inventory database [21], considering the Portuguese 2022 Conjunctural Land Cover Map (COSc) [22] (Appendix B). 2. Belowground carbon storage, i.e. carbon stored in the soil, was assessed considering the 2015 and 2018 LUCAS database [23, 24, 25], namely the organic matter values (in %) from all sampling points of inland Iberia Peninsula (N=2500) that were used in a co-kriging analysis [26], using Carbon in soil as primary variable and use secondary variables in spatial cross-correlation to enhance the prediction accuracy. Spatial modelling was performed by Co-kriging as Ramos et al. (2017) [27] work using a set of environmental soil-related covariates (elevation, land use, soil units and parent material); this approach is commonly applied in soil science studies [28].

The information was spatially summarised for the four ES considering the European 1km reference grid [29].

2.2.2 ES synergies and mismatches

A hot spot analysis was also performed, using the Getis-Ord G_i* statistic, to understand the ES spatial patterns (Equation 1). This statistical method identifies clusters of high and low values (hot and cold spots, respectively) in several ecological contexts. The clusters are formed by their statistical significance, with a high z-score representing statistically significant hot spots (90%, 95% and 99%) and a low z-score representing statistically significant cold spots (90%, 95%, and 99%). Non-significant areas with z-scores close to 0 are considered neutral, with no significant clustering.

$$G_i^* = \frac{\sum_{j=1}^{n} w_{1,j} x_j - \bar{X} \sum_{j=1}^{n} w_{1,j}}{S \sqrt{\frac{\left| n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{1,j}\right)^2 \right|}{n-1}}} \quad (1)$$

Where:

n is equal to the number of features

x_j is the attribute value for feature j,

$\bar{X}$ represents the average of x_j

$W_{i,j}$ is the spatial weight between features i and j,

S the standard deviation of x_j

The hot and cold spot data were used to identify synergies and mismatches based on a Spearman's rank correlation was used to measure the strength and direction of the association between each pair of ESs. To do so, all the cells with confidence values greater than or equal to 90% were considered in the analysis, having been reclassified as 1 (in the case of hot spots) and -1 (in the case of cold spots). The areas where two ES hot spots overlap reveal a potential synergy, while areas with hot and cold spots co-occurrence indicate mismatches between those ES.

3. RESULTS AND DISCUSSION

3.1. Provision of ecosystem services

The spatial representation of the 4 ES assessed and the hot and cold spots for each ES can be observed in Figure 3 and Figure 4, respectively.

Although the cultivated plants for nutrition (P1) were evenly distributed throughout the territory, some of the subregions (East and West mountainous and Tagus subregions) showed several grid cells without crop production. The study area had more than a quarter (27%) without P1 provision, primarily located in protected areas, that are P1 cold spots. In more than half of the squares, the mean production was less than 0.5 tons/ha (53%) and around 16% produce less than 2 tons/ha. The highest values (P1 hot spot) were found in the 'Cova da Beira' and some areas of Southern plain (3% have up to 4ton/ha and 1% more than 4 ton/ha). Both sub-regions have irrigated land and more intensive farming. Irrigation significantly enhances food production and is crucial for global food security since it provides 40% of the world's crop-based foods [30]. However, to not compromise other ES, sustainable management practices are crucial to mitigate the environmental impacts of intensive production, namely efficient water use and reducing soil management, which are key to maintaining the benefits of irrigation in agricultural systems [31].

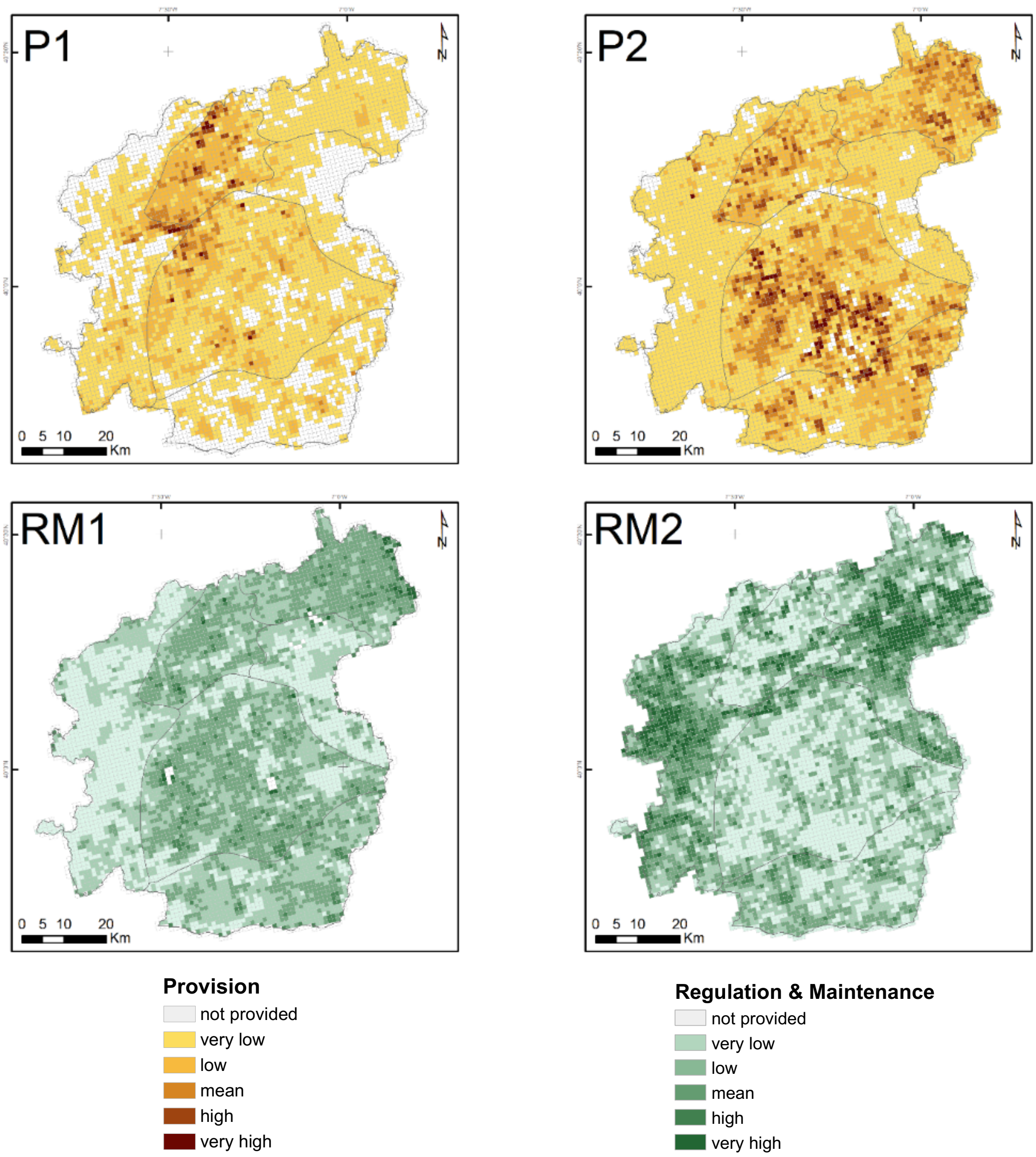

Figure 3. Spatial representation of the 4 ES was assessed using natural break clustering: P1 – cultivated terrestrial plants for nutrition; P2 – reared animals for nutrition; RM1 – Regulation of soil quality; RM2 – Climate regulation. Cells that did not provide ES are in white. The remaining cells represent the scale of provision based on a colour gradient (lighter- less provisioned; darker - higher provision).

Only 6% of the area have no animal production (P2), but around half of the cells (54%) have few livestock (less than 0.1 NH/ha), being those cells primarily located in the mountainous regions (both east and west). Approximately 24% have up to 0.5 NH /ha, especially in the Tagus region and the East-northern plateau, around 5% have up to 1 NH/ha and only 1% exceed that amount. The P2 hot spots primarily occur in the 'southern plain', followed by 'Cova da Beira', where agroforestry systems known as 'Dehesa' are prevalent. The 'dehesa' systems, typical of the southwestern Iberian Peninsula, are characterised by extensive livestock farming, vital for those regions' economic and environmental sustainability [32, 33]. There is also a hot spot on the east side of the northern plateau, where other agroforestry systems are predominant: the 'Bocage landscapes', characterised by a patchwork of fields, hedgerows, woodlands and livestock. This traditional form of agroforestry creates a continuous network of meadows and fields bordered by living hedges, that help manage livestock movement and provide fodder, thereby supporting livestock productivity and well-being [34, 35, 36].

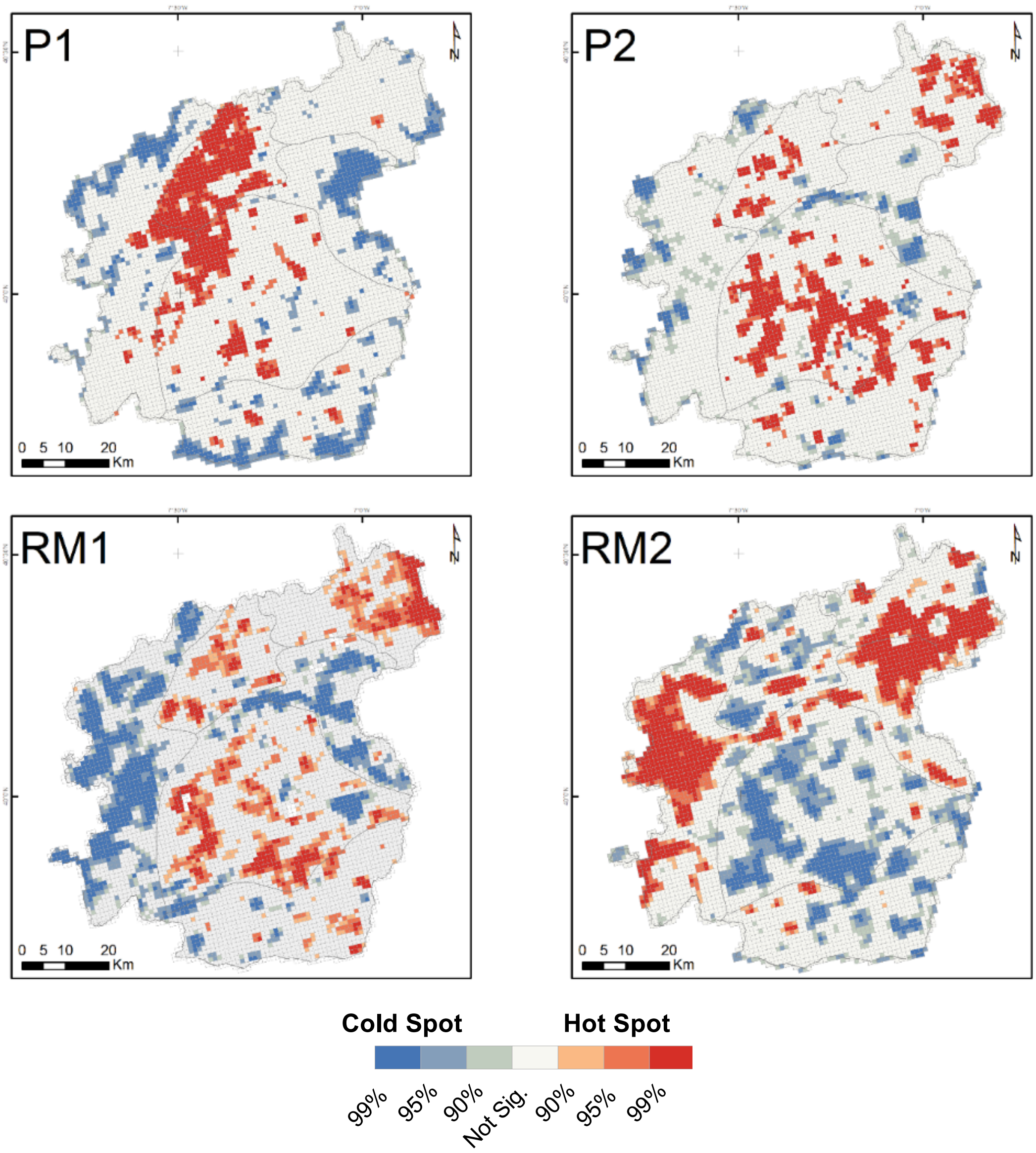

Figure 4. Ecosystem services Hot and Cold Spots for: P1 – cultivated terrestrial plants for nutrition; P2 – reared animals for nutrition; RM1 – Regulation of soil quality; RM2 – climate regulation, Color gradient: variates with statistical significance (90%, 95%, and 99%), Clod (BLUE) and Hot (RED).

Considering soil quality, more than half of the area has ‘very good’ or ‘good’ quality soils (59%), especially in ‘Cova da Beira’, Southern Plain and Northern Plateau, where most hot spots were identified. About a third of the study area (32%) has intermediate soil quality, mainly in the Tagus region. The remaining 9% has low or very low soil quality, being those cold spots mainly associated with the mountainous regions. Topography is a significant factor affecting soil properties, including the C/N ratio. Flatter areas, such as 'Cova da Beira', the Southern Plain and the Northern Plateau, tend to have better soil quality due to more stable conditions that favour nutrient accumulation. In contrast, steeper areas, such as the two mountainous regions and the Tagus region, often experience erosion and nutrient loss, leading to lower soil quality [37, 38].

Regarding climate regulation (RM2), assessed based on carbon stock and sequestration, 31% of the study area a very low contribution to climate regulation (less than 3,5 tC/ha/yr, 26% have a low contribution (up to 5,5 tC/ha/yr), 24% have a mean contribution (up to 8,5 tC/ha/yr) and 13% have a high contribution (up to 12 tC/ha/yr), with 6% presenting a very high contribution (more than 12 tC/ha/yr). The cold spots are primarily in 'Cova da Beira', Southern Plain, and some parts of the Tagus region while most of the hot spots are in the mountainous areas. These results are largely due to the fact that forests are more commonly found in mountainous regions, with a notable amount of forest land located on slopes exceeding 15°[39].

3.2. Synergies and mismatches between ES

The Spearman's correlation analysis (ρ) reveals that all ES were significantly correlated with each other (Table 1). We found a positive correlation between both provisioning services and soil quality (ρ ranging between 0.23 to 0.53) being mostly weak correlations, with the exception between P2 and RM1, with a moderate correlation. RM2 was negatively correlated with the other 3 ES (weak correlation). At a geospatial level, these positive and negative correlations are shown in Figure 5, which presents the synergies and mismatches between each pair of ecosystem services.

Table 1. Spearman's correlation analysis between the assessed ES

Spearman's RS	P1	P2	RM1	RM2
P1	1			
P2	0.23*	1		
RM1	0.35*	0.53*	1	
RM2	-0.25*	-0.30*	-0.31*	1

*$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

The main mismatches occur between climate regulation (RM2) and the other three ES, with the discrepancies being most evident with soil quality (RM1), especially in the two mountainous areas (wherein 30% of those regions, the RM2 hot spot coincides with the RM1 cold spot) and in ‘Cova da Beira’ (where in the 20% of the area the RM1 hot spot coincides with RM2 cold spots). Regarding livestock production, the main mismatches occur in all sub-regions (10-20% of the area), except in the northern plateau and Tagus region. Those two regions feature traditional agroforestry systems such as ‘dehesa’ and ‘bocage’ landscapes, which provide a good trade-off between P2 and RM2 [40, 41]. Another exception occurs in the northern slopes of the Eastern mountains, with synergies between P1 and RM2. Due to their particular soil and climate conditions, in addition to forest plantations this area also have a large number of mountainous orchards (cherry stands).

In terms of agricultural production, mismatches were primarily found in 'Cova da Beira', where 30% of the area displays a coincidence of P1 hot spots with RM1 cold spots. Additionally, in the East mountains, 20% of the region shows RM1 hot spots overlapping with P1 cold spots.

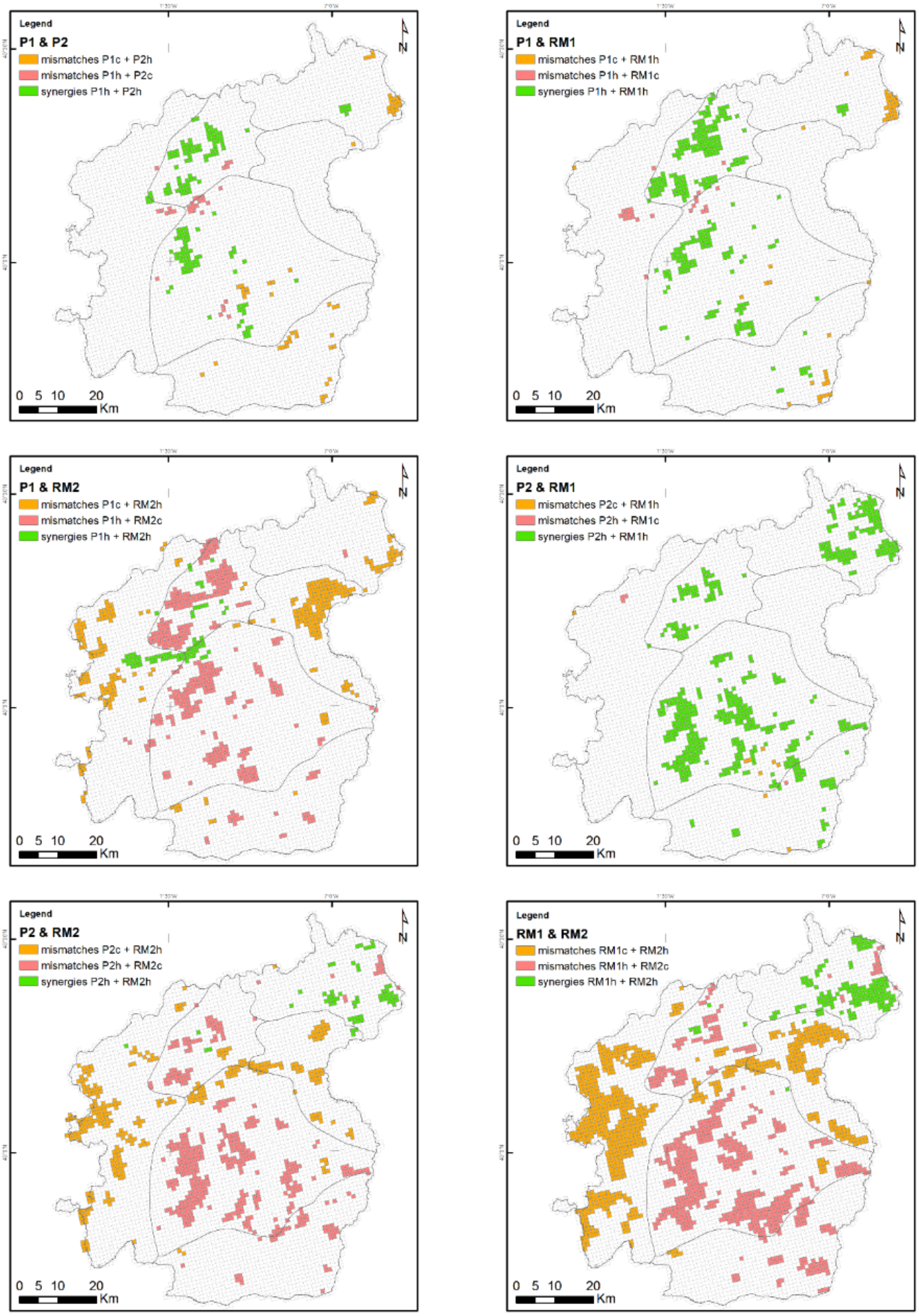

Figure 5. Synergies and mismatches between the four ecosystem services. Mismatches_*ES*cold+*ES*hot (orange); Mismatches_ *ES*hot+*EScold* (pink) and Synergies_ *ES*hot+*ES*hot (green).

The synergies occur mostly between livestock production and soil quality, especially in the Southern plain and northern plateau, where 17% and 16% of the squares have hot spots for both services. In 'Cova da Beira' the most significant synergies are observed between agricultural production and soil quality or livestock production (28% and 14% of hot spot areas overlapping, respectively). These results are mainly driven by rural exodus and agriculture abandonment, which can lead to natural succession and the growth of native forests on once-farmed good, gently sloping soils [42].

The northern plateau also exhibits synergies between climate regulation (RM2) and soil quality (RM1), with 18% of the grid cells being hot spots for both ES. Additionally, there is a 7% coincidence of hot spots between livestock farming (P2) and soil quality (RM2). These results are deeply linked with the extensive cattle production in the 'Bocage' agroforestry system, which provides a favourable trade-off between climate regulation and livestock farming. Other authors have found that livestock farming contributes to soil fertility and carbon sequestration, although there may be trade-offs with other ecosystem services such as crop production [43, 44].

These synergies and mismatches information can guide targeted conservation efforts and inform regional development planning by highlighting areas of ecological importance and potential conflicts among different ecosystem services. Recognising these spatial and temporal dynamics is essential for sustainable ecosystem management and policy-making [45, 46, 47, 48].

4. CONCLUSIONS

There are noticeable variations in ES distribution within the sub-regions under study. Crop production is low and widespread, except in Cova da Beira and the Southern Plain, where irrigated areas play a key role in high-yield areas. Livestock production is more localised, especially in agroforestry systems ('dehesa' and 'bocage landscapes'), which also have an important role in climate regulation. This aspect is particularly relevant since, in general, climate regulation follows the opposite pattern of the other three ES, with stronger contributions in forested, elevated regions and lower values in intensively farmed areas. Thus, our results emphasise the relevance of diversifying agricultural and forestry practices by promoting traditional agroforestry systems that have shown a good trade-off between climate regulation and food production. These highlight the importance of adopting sustainable land-use strategies to optimise ES trade-offs while ensuring productivity and environmental resilience. Addressing the risks of climate change and environmental degradation requires promoting sustainable practices. Additionally, long-term food security depends on balancing ecological health and agricultural productivity. These include community involvement in sustainable land use management, which should foster better cooperation between farmers, legislators, researchers, and other stakeholders to increase agroforestry areas that can handle present demands and upcoming challenges.

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Appendix A. List of Species and the effective relationship between livestock unit (LU) and LULC classes.

Species	***LU***	***N. animal /ha***	***LULC***
Cattle	1	2	Grassland
Goats	0.150	14	Srubland, grassland, or permanent crops associated with grassland, Annual culture associated with grassland
Sheep	0.150	14	Grassland, Permanent crops associated with grassland, Annual culture associated with grassland
Pigs	0.30	8	Agroforestry, Grassland

Appendix B. Carbon information by land uses (COSc), considering INF, 2019.

COSc2022	***CLC***	***carbon/ha***
100	Artificial land	0.81
210	Agriculture. winter temporary crops	11.28
212	Agriculture. summer temporary crops	11.28
213	Agriculture. permanent crops. managed grassland. and lawns	11.28
311	Evergreen oaks: Cork oak (*Quercus suber*) and Holm oak (*Quercus rotundifolia*)	128.94
312	Eucalyptus (*Eucalyptus* spp.)	99.88
313	Other broadleaves	250.66
321	Maritime pine (*Pinus pinaster*)	155.60
322	Stone pine (*Pinus pinea*)	201.83
323	Other conifers	174.69
410	Shrubland	29.87
420	Spontaneous herbaceous vegetation	29.87
500	Bare soil. rocks or sand	0.48
620	Water	0.00