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Synergies and trade-offs among ecosystem services for climate neutrality: Lessons from Campania, Italy

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Abstract: Understanding synergies and trade-offs among ecosystem services is vital for designing effective climate neutrality strategies that avoid unintended impacts in multifunctional areas. Using the Campania Region (Italy) as a case study, this research proposes a methodological framework to analyze the synergies and trade-offs between six ecosystem services. The approach is structured in two phases: (i) spatial mapping and quantitative assessment of the selected ecosystem services, and (ii) estimation of pairwise Spearman's rank correlation coefficients to identify statistically significant synergies and trade-offs. The findings offer valuable insights to inform spatial policies that minimize conflicts and maximize co-benefits among ecosystem services.

Keywords: Ecosystem Services, Climate Neutrality; Ecosystem Service Synergies; Regional Planning; Mitigation and Adaptation Measures

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1. Introduction

Climate neutrality strategies increasingly rely on the multifunctional role of Ecosystem Services (ESs), which offer simultaneous co-benefits for climate mitigation and adaptation, biodiversity and human well-being [1]. However, interactions among ESs can manifest either as synergies, when the enhancement of one service reinforces others, or as trade-offs, if the improvement of one service diminishes others [2]. Understanding these interactions is therefore critical for designing integrated strategies that promote beneficial synergies and mitigate conflicts [3]. This study applies a two-step methodology to Campania, a region in Southern Italy, as follows: (i) spatial mapping and quantitative assessment of six ESs, including carbon storage (CS), habitat quality (HQ), ground temperature (GT) regulation, agricultural and forestry production value (PV), landscape value (LV), and recreation value (RV); and (ii) estimation of pairwise Spearman's rank correlation coefficients to identify statistically significant synergies and trade-offs. The results aim to guide regional planning strategies toward climate neutrality.

2. ESs Spatial taxonomy

ESs are mapped and assessed through different methods as follows.

CS is evaluated through the InVEST "Carbon Storage and Sequestration" model, which estimates CS across four pools (aboveground, belowground, dead organic matter, and soil) [4]. CS varies from 0 to 21.54 Mg per 900 m². The highest values are concentrated in protected areas, while artificial surfaces and water bodies store less than 1 Mg.

GT is derived from the thermal B10 band of the Landsat 8–9 OLI/TIRS C2 Level 2 imagery obtained through the USGS Earth Explorer platform [5]. Multiple raster images of summer 2023 are processed. GT values vary from 27.5°C to 64.5°C, peaking in urban and agricultural areas and decreasing significantly along the Apennines.

HQ is assessed via the InVEST HQ model [6], whose calculations are based on land use and land cover classification, types and characteristics of environmental threats, proximity of habitats to these threats, and habitat suitability and sensitivity [7]. Results are expressed on a unitless scale from 0 (non-habitat) to 1 (optimal quality), producing a continuous gradient map illustrating habitat condition across the region [7,8]. The highest HQ values are concentrated in forested areas, while the lowest are in urbanized areas and intensively cultivated lands. The regional mean is 0.49, with 31% of the territory classified as high-quality, 28% as intermediate-quality, and 41% as low-quality habitat.

PV is estimated from the monetary value of land [8]. Mean agricultural land values were sourced from the Italian Council for Agricultural Research and Economics (CREA), while forestry values were derived from the 2023 mean agricultural values published by the National Revenue Agency. Spatial analysis links these values with the classes of the CORINE Land Cover 2018 to obtain the PV values, which range from zero in non-productive land to €82,316/ha in the fertile plains of the Sorrento Peninsula and the coastal hills of Naples, dominated by horticultural and arable crop cultivation.

LV is evaluated for its scenic value by using the InVEST scenic quality model, which combines the regional digital elevation model with georeferenced visual disamenities, renewable energy infrastructure, in this study [9]. LV is reported as a unitless score from 0 to 4, representing conditions from unaffected to severely impacted by visual disamenities, and is visualized through a gradient map depicting its spatial distribution [9]. The regional mean value is 1.33, where preserved landscapes, concentrated within protected areas, characterize 54% of the territory and poor-quality landscapes, associated with agricultural landscapes, account for 11% of the region.

RV is quantified by using the ESTIMAP GIS-based approach [8,10], which integrates the availability of accessible recreational areas, the presence of attractive natural and landscape features, and proximity to coastal elements to produce a composite index ranging from 0 (very low potential) to 3 (high potential). RV values range from 0.1 to 3, reaching the highest levels along the non-metropolitan coastline and within protected areas and the lowest scores in inland agricultural zones.

3. Spearman's correlations

Spearman's correlations (ρ) evaluate the relationship between the ranks of two variables and therefore represent an appropriate non-parametric tool for assessing interactions between pairs of ESs, specifically for analyzing synergies (positive correlations) and trade-offs (negative correlations) [11,12]. The correlation coefficient ρ between two ESs (ES_1 and ES_2) is calculated through the equation (1):

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad (1)$$

where:

- d_i is the difference between the ranks of $v_{1,i}$ and $v_{2,i}$;
- $v_{1,i}$ and $v_{2,i}$ are the values of ES_1 and ES_2 at the same location $i (i = 1, \ldots, n)$;
- n represents the total number of observations, or spatial units over which the two ESs are assessed.

In this study, n=343,380, corresponding to the total number of 200 m × 200 m vector grid cells covering the entire Campania Region. For each cell, the mean values of the six ESs described in Section 2 were computed using zonal statistics and assigned as attributes. These attributes were then used to calculate ρ for every ES pair across the total n observations, according to Equation (1). As illustrated in Table 1, the calculated Spearman's correlations exhibit high statistical significance (p-value < 0.05). Strong positive correlations ($\rho \approx 0.80$) are observed among CS, GT, and HQ, indicating substantial synergies. These three regulating services also exhibit moderately strong positive correlations ($\rho \approx 0.70$) with RV. In contrast, correlations between these four ESs and PV and LV are weak and generally insignificant, with ρ below 0.23.

Table 1. Spearman's correlation results

Variable	Correlation	t-Statistic	p-Value
CS-GT	-0.8212	843.3883	0.0000
CS-HQ	0.8993	1205.4239	0.0000
CS-PV	-0.0391	22.9469	0.0000
CS-LV	-0.1926	114.9973	0.0000
CS-RV	0.6791	542.0398	0.0000
GT-HQ	-0.7836	739.1839	0.0000
GT-PV	0.0757	44.4580	0.0000
GT-LV	0.2076	124.3740	0.0000
GT-RV	-0.6695	528.0852	0.0000
HQ-PV	-0.1420	84.0434	0.0000
HQ-LV	-0.1551	92.0268	0.0000
HQ-RV	0.6850	550.9167	0.0000
PV-LV	-0.0377	22.1047	0.0000
PV-RV	-0.0999	58.8268	0.0000
LV-RV	-0.2282	137.3385	0.0000

Means of variables CS, GT, HQ, PV, LV, RV: 87.9987, 42.4707, 0.4984, 16484.5664, 0.3313, 0.3151

Standard deviations of variables: 56.2534, 5.8240, 0.2671, 13883.7465, 0.3626, 0.1811

4. Discussion and conclusion

Results suggest that progress toward global climate neutrality, proxied here by increased CS, is closely linked to GT mitigation and to habitat conservation. Local climate regulation and HQ, in turn, support greater availability of nature-based recreation opportunities. Overall, the findings indicate that global and local climate mitigation, ecological health, and opportunities for recreational activities in natural context are synergistic ESs. These synergies are consistent with a broad body of international literature, which confirms the patterns observed in Campania across diverse geographical contexts and methodological approaches. For example, studies conducted in India, Ethiopia, and China demonstrate that increases in CS correspond to measurable reductions in GT [14-16]. This evidence reinforces the central role of green spaces in mitigating extreme heat and urban heat island effects. Furthermore, the negative correlation observed in Campania between GT and HQ aligns with numerous studies identifying heat stress as a primary threat to ecosystem health and species viability [17,18]. This emphasizes the importance of preserving and enhancing natural landscape elements that play a critical role in regulating local climate, even outside protected areas.

Conversely, the positive association between CS and RV identified in Campania remains debated in the literature. While it is consistent with synergies reported in California [19] , it contrasts with trade-offs observed in regenerated post-mining landscapes in Germany [20] and in dense forests limiting accessibility in China [21]. These contrasting findings suggest that the CS–RV relationship is highly context-dependent, determined by land-use history, forest structure, and the spatial configuration of green spaces. Nonetheless, policy implications are clear: strategies aimed at jointly supporting CS and RV should move beyond simple green-space preservation and instead promote diversified, accessible, and well-connected vegetated areas, that combine high CS potential with enhanced accessibility.

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