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RESEARCH ARTICLE

Handling ecosystem service trade-offs: the importance of the spatial scale at which no-loss constraints are posed

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Abstract
Context Managing land use to promote an ecosystem service (ES) without reducing others is challenging. The spatial scale at which no-loss constraints are imposed is relevant.
Objectives We examined the influence of the spatial scale of no-loss constraints on ESs when one ES was optimised. Specifically, we investigated how carbon sequestration could be maximized at different spatial scales in France with constraints of no-loss on other ESs.
Methods We used a statistical model linking land use and land cover variables to ESs [carbon sequestration (CS), crop production (CP), livestock production, timber growth] in French small agricultural regions (SARs). We optimised CS at the country scale posing no-loss constraints on other ESs at increasing spatial scales, i.e., SARs (scenario 'SARs'), department ('DEP'), administrative region ('REG'), and France ("FRANCE"). We analysed differences between optimized and initial configurations.
Results Optimized CS at the country scale increased with the spatial scale at which no-loss constraints were posed (~+0.51% for 'DEP' and ~+2.05% for 'FRANCE'). The variability of ES variation among the SARs similarly increased. This suggested that constraints at larger scales lead to ES segregation. Correlations among ES variations changed with the scenarios (Spearman's ρ between CS and CP was −0.43 for 'DEP' and −0.70 for 'FRANCE'). This indicated that different land use strategies produce different degrees of enhancement/softening of ES trade-offs/synergies.
Conclusions A trade-off was highlighted: larger spatial scales promoted better performance of the target ES but also spatial inequality. We argue that addressing smaller scales will lead to land-sharing solutions that avoid the local environmental impacts of land-sparing strategies.

Keywords Ecosystem services trade-offs · Optimization · Strong sustainability · Multi-scale analysis · Land use strategy

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Introduction

Ecosystem services (ESs) are increasingly considered in policy and decision-making (Bouwma et al.

2018) as advised by scientists, such as in the Millennium Ecosystem Assessment (MEA 2005). ESs and their relationship with landscapes have a key role in landscape sustainability science (Musacchio 2013; Potschin and Heines-Young 2013; Wu 2013). However, a challenge has arisen in conciliating provisioning services (e.g., agricultural and timber production, more related to the manufactured, human-made capital) with regulating services (e.g., carbon sequestration, more related to the natural capital). Increasing agricultural production to meet increasing food demand, for instance, should not harm the provision of other ESs (Ericksen et al. 2009; Godfray et al. 2010; Foley et al. 2011) and vice versa.

Trade-offs impede conciliation between different ESs (Bennett et al. 2009), especially between provisioning and regulating. A trade-off occurs when the increase in the provision of one ES has negative consequences for another ES (Rodríguez et al. 2006). Many trade-offs are linked to land cover changes (Ruijs et al. 2013) because each land cover type provides a certain set of ESs; land is a scarce resource, so the expansion of one land cover type usually results in a reduction of a competing land cover type and its associated ESs (Metzger et al. 2006). The concept of ES trade-off can be crossed with sustainability science. Following Wu (2013, 2019), according to weak sustainability, natural and manufactured (human-made) capitals are substitutable, therefore an improvement in one can come at the expense of another. In contrast, strong sustainability aims at improving aspects of the total capital without reducing other aspects (natural and manufactured capital are not substitutable). Therefore, considering ES trade-offs in a paradigm of weak sustainability allows maximizing one ES with a possible loss of other ESs; in contrast, in a paradigm of strong sustainability the maximization of one ES should occur under constraints of no-loss of other ESs.

The spatial scales at which ES trade-offs and multifunctionality are studied have received attention. Some research has noted that studies of ES trade-offs often choose scales arbitrarily, failing to sufficiently consider scale-related issues (Mastrangelo et al. 2014; Lindborg et al. 2017; Stürck and Verburg 2017). Furthermore, considering only one scale often leads to incomplete or even distorted conclusions (Raudsepp-Hearne and Peterson 2016). For these reasons, studies are increasingly advocating for assessments to consider multiple scales at once (Scholes et al. 2013; Anderson et al. 2015; Qiu et al. 2017; Raudsepp-Hearne and Peterson 2016; Hölting et al. 2019), ultimately raising the question of the scale at which ESs are most effectively managed (Mastrangelo et al. 2014).

Scaling issues have received great attention in landscape ecology (Frazier et al. 2022), especially regarding how the spatial scale of analysis affects results. An important concept related to this is the Modifiable Area Unit Problem (MAUP), according to which the results of the analysis are affected by the spatial grain and the extent considered (Wu 2004). Several studies focused on scalograms, which describe how particular landscape properties change with the scale considered (Bar Massada and Radeloff 2010; Ma et al. 2019; Sun et al. 2022; Liu et al. 2023). To give an example, Sun et al (2022) demonstrated that land use and land cover variables, along with the ESs provided, varied with the radial distance considered around a city center. Scale issues have also been addressed and discussed in ES mapping (Grêt-Regamey et al. 2014; Moindjié et al. 2022), ES modelling (Qiu et al. 2017), multifunctionality measurements (Stürck and Verburg 2017), landscape metrics (Wu 2004; Frazier 2022). In particular, Qiu et al. (2017) modelled ES provision in future scenarios and quantified the trade-offs among ESs at different scales within a watershed in Wisconsin. Their results show that relationships among some of the ESs were consistent across scales, but others had scale-dependent relationships. Stürck and Verburg (2017) tested a set of ES multifunctionality indicators at various scales and concluded that no one indicator was more accurate than the others but further noted that considering indicators at different scales could affect the results and implications.

This study aimed to address an additional issue. We hypothesised that strong sustainability at a country scale can be achieved by management at different smaller spatial scales, producing different results. In other words, a country represents a hierarchical system formed by territorial units and subunits, so the pursuit of no-loss ES management can target both the national scale and the spatial scales corresponding to each unit and subunit. Such consideration being made, this research aimed to address the following question: *when maximising one ES at the country scale, how does the spatial scale at which* *no-loss constraints are imposed on other ESs play a role?* This corresponds to framing a strong sustainability problem at different scales: which are the consequences of addressing strong sustainability at different scales? In addition, we also pose the following question: *are trade-offs and synergies among ESs softened or enhanced at different spatial scales at which no-loss constraints are posed?* Modelling can help to address these questions as it allows linking ES drivers (e.g., land use) to ES outputs (Nelson et al. 2009; Tallis and Polasky 2011). Furthermore, coupling modelling with optimisation methods can produce a combination of drivers that maximises a target ES (objective) under certain constraints (Seppelt et al. 2013; Accatino et al. 2019). Optimisation strategies that have been applied to models in the ES literature include mono-objective optimisation with constraints on other objectives (Butsic and Kuemmerle 2015; Accatino et al. 2019) and multi-objective optimisation (Groot et al. 2012; Teillard et al. 2017; Shi et al. 2021).

We investigated the effect of the spatial scale at which ES no-loss constraints are imposed to obtain no-loss ES management strategies at the country scale (here, France), while optimising one ES. More precisely, in line with initiatives started in France, namely the '4 per 1000' initiative (Kon Kam King et al. 2018), which encourages stakeholders to find solutions for progressive carbon storage in soils, we aimed at maximising carbon sequestration in France using a model that imposes no-loss constraints on other ESs and constraints of no further intensification at different spatial scales, namely the small agricultural region (SAR), the department (corresponding to the Nomenclature of Territorial Units for Statistics [NUTS]3), administrative region (NUTS2), and country. We analysed the extent to which carbon sequestration could be optimised for all of France by imposing constraints on the other ESs at each spatial scale considered and investigated the consequences for the other ESs within the spatial units. This corresponds to a MAUP, as we observe the effect of the spatial extent in which the optimization problem is framed. A similar multi-scale optimization analysis was done by Pohjanmies et al. (2017) involving the multi-criteria optimization of timber extraction and carbon storage, at the scale of small holding, large holding, and watershed, and region. We also examined the correlations among the variations of ESs to investigate how the intensities of trade-offs and synergies among them varied at each spatial scale. We used a model previously defined and parameterised in the literature (Accatino et al. 2019), which links land cover, land use and climatic variables to ES provision. Insights from the present study highlight the consequences of seeking win/no-loss solutions at certain spatial scales and suggest considerations for future studies seeking the optimal spatial scale to address.

Materials and methods

Model description

We adopted the model developed by Accatino et al. (2019) for this study, which is briefly re-described here. Metropolitan France is divided into 714 SARs—territorial units characterised by homogeneous agronomic and pedological conditions. Their boundaries are coincident with the departmental (NUTS3) and regional (NUTS2) boundaries, i.e., a SAR does not intersect multiple departments or regions and may share part of the boundary. For this study, a management area S (ha) was defined for each SAR and divided into land use fractions ϕ_l with $l \in \{C, FOD, TG, PG, F\}$, corresponding to cropland, fodder land, temporary grassland, permanent grassland and forest, respectively. Each land use fraction was in the range 0–1, and the sum of all fractions for each SAR was 1. The management areas could be smaller than the actual surface of a SAR because some land cover types were not considered in the model. Cropland and fodder land represent the annual crops cultivated for human and animal consumption, respectively, and temporary grassland is cultivated with harvested grass. Permanent grassland and forest were further divided into subcategories $\varphi_{i,l} \in \Gamma_l$, where Γ_l is the set of sub-fractions of land cover type l. Following the Corine Land Cover (CLC) classification (EEA 2013), permanent grassland was divided into *Pasture* (CLC 231) and *Natural Grassland* (CLC 321) and forest was divided into *Broad Leaved Forest* (CLC 311), *Coniferous Forest* (CLC 312), *Mixed Forest* (CLC 313), *Sclerophyllous Vegetation* (CLC 323) and *Transitional Woodland/Shrub* (CLC 324). Cropland, fodder land and temporary grassland had only one sub-fraction each, equal to 1.

We also considered other variables, including pesticide expenses (an indicator of agricultural intensification) for cropland θ_{PC} (€ ha^{-1} year^{-1}) and fodder land θ_{PFOD} (€ ha^{-1} year^{-1}), average crop energy content θ_E (Mcal ha^{-1}) and climatic variables, namely rainfall θ_R (mm year^{-1}) and temperature θ_T (°C). The ESs considered were carbon sequestration (CS), crop production (CP), livestock production (LP) and timber growth (TG).

The model's equations do not represent mechanistic processes but rather black-box relationships among variables with data-calibrated parameters. The provision of each ES $E_{k,j}$ ($k \in \{CS, CP, LP, TG\}$) in each SAR j is given by:

$$E_{k,j} = S_j \sum_{l \in L} \phi_{l,j} \cdot \sum_{i \in \Gamma_l} \varphi_{i,l} \cdot f_{i,l,k}(\theta_{PC,j}, \theta_{PFOD,j}, \theta_{E,j}, \theta_{R,j}, \theta_{T,j}) \tag{1}$$

Equation (1) assumes that each sub-fraction of each land cover type produces a specific quantity of ES k, dependent on the land use and climatic variables. The total ES produced in each SAR is given by the sum of the contributions of each land cover type. The function $f_{i,l,k}(\cdot)$ represents the influence of land use and climate variables on the provision of each ES k by the sub-fraction i of land cover l in the form of a Cobb–Douglas function (Accatino et al. 2019; Shi et al. 2021).

$$f_{i,l,k}\left(\theta_{PC,j}, \theta_{PFOD,j}, \theta_{E,j}, \theta_{R,j}, \theta_{T,j}\right) = \alpha_{i,l,k} \cdot \prod_{n \in N} \theta_{n,j}^{\gamma_{n,i,l,k}} \tag{2}$$

where $N = \{PC, PFOD, E, R, T\}$. The data used, the calibration procedure and the parameter values are detailed in Accatino et al. (2019).

Optimisation scenarios

Optimisation starts from an initial configuration of variables. Some variables are chosen as 'driving variables' (Accatino et al. 2019) and systematically changed to optimise the output accounting for the imposed constraints until an optimised configuration is reached. In our study, the initial configuration of variables in the SARs was derived from the data (see Accatino et al. (2019) for more details), and the driving variables were defined as the land cover fractions and pesticide expenses for cropland and fodder land. The variables not chosen as driving variables were considered as constants during the optimisation procedure, as in the initial configuration.

Scenarios were designed to answer the main research question—*how does the spatial scale at which no-loss constraints are imposed influence the achievement of no-loss ES management at the country scale?* We performed a mono-objective (i.e., carbon sequestration) optimisation with no-loss constraints on other objectives (i.e., other ESs). In each scenario, the objective was maximised for all of France and constraints were imposed at different spatial scales: other ESs were forced not to decrease and pesticide expenses were forced not to increase. This optimisation is defined with:

$$\begin{aligned} & max\left(\sum_{j \in F} E_{CS,j}\right) \\ & \sum_{j \in \Omega_h} E_{k,j} \geq \sum_{j \in \Omega_h} E^0_{k,j} \quad \forall h, \forall k \in \{CP, LP, TG\} \\ & \sum_{j \in \Omega_h} \Theta_j \leq \sum_{j \in \Omega_h} \Theta^0_j \quad \forall h \end{aligned} \tag{3}$$

where F represents all the SARs in France; Θ_j is the total pesticide expenses (in cropland and fodder land) in SAR j; and Ω_h represents sets of SARs and is distinct for different scenarios. In the first scenario ('SARs'), Ω_h represents each SAR; in the second scenario ('DEP'), Ω_h represents each metropolitan French department (NUTS3); in the third scenario ('REG'), Ω_h represents each metropolitan French administrative region (NUTS2); and in the fourth scenario ('FRANCE'), a single $\Omega_h = F$, corresponding to all the SARs in France. Figure 1 presents the boundaries within which the no-loss constraints were applied. Other SAR-specific constraints, described in Accatino et al. (2019), were applied to limit the maximum extent to which the driving variables can be modified.

For each scenario, some notable outputs provided insights into the effect of spatial scale on our optimisation exercise. First, we observed the total increase in carbon storage at the country scale. Second, the boxplots and maps showed the variability in ES changes across the SARs for all ESs considered. Third, we observed co-variations of the ESs, which were quantified with the Spearman coefficient

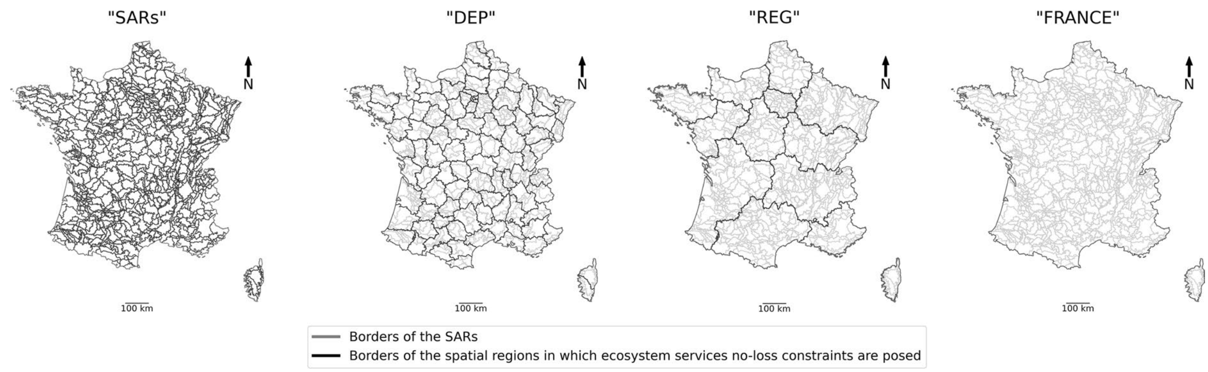

Fig. 1 Boundaries of the spatial units at which no-loss constraints in the four scenarios were applied to the considered ecosystem services (carbon sequestration, crop production, livestock production, timber growth) while carbon sequestration was maximised at the country scale. From left to right, the boundaries correspond to small agricultural regions ('SARs'), French departments ('DEP'), French administrative regions ('REG') and France. In light gray, the SARs boundaries (the spatial resolution of the model) are provided for the 'DEP', 'REG' and 'FRANCE' scenarios. French departments correspond to the Nomenclature Units of Territorial Statistics (NUTS)3, and French administrative regions correspond to NUTS2

ρ (ranging from -1, perfect negative correlation, to $+1$, perfect positive correlation) and indicate the trade-offs and synergies among the ESs. We defined strong relationships as those with $\rho < -0.5$ (negative) and > 0.5 (positive). Although some ES trade-offs or synergies have been quantified using correlations among the data or cluster analyses (see Raudsepp-Hearne et al. 2010; Jopke et al. 2015; Mouchet et al. 2017), we examined correlations in the results of an optimisation exercise performed with a model that linked drivers to ES, thereby considering causality (Groot and Rossing 2011; Accatino et al. 2019).

Results

Changes in ecosystem services

The results showed that no-loss constraints imposed at larger spatial scales allowed for greater improvement of the optimised target ES at the regional scale (Fig. 2). A weak increase in carbon sequestration was noted in the 'SARs' scenario, whereas progressively better performances were achieved in the 'DEP', 'REG' and 'FRANCE' scenarios, with the latter obtaining the best performance.

The variability of the ES variations observed among the SARs increased with the spatial scale at which constraints were imposed for all ESs (Fig. 3). The 'SARs' scenario was the only one to show no negative variation for ES, which is congruent with the scenario definition (i.e., no loss of any ES at the SAR scale). The 'DEP' scenario showed weak variability with some negative variations at the SAR scale. High variability was observed in the 'REG' and 'FRANCE' scenarios, meaning that local increases in ESs were achieved alongside some local reductions in other ESs. Among all ESs, timber growth showed the least negative variation, mainly due to the strict constraints imposed on forest reductions in the optimisation model.

We mapped the results for the 'REG' and 'FRANCE' scenarios with the same colour scale for each ES (Fig. 4); SAR-scale variations in the 'SARs' and 'DEP' scenarios were too weak to be observed with the same colour scale. There are evident differences between the 'REG' and the 'FRANCE' scenarios. In the 'FRANCE' scenario, the administrative regions showed high degrees of specialisation, meaning that the SARs in these areas saw a simultaneous increase in one ES and a decrease in another. This is the case, for example, in the north-western part of France, where carbon sequestration increased in all the SARs as crop and animal production decreased. Other groups of SARs presented opposite specialisation, such as in the centre-sounth and in the south-western part of France. ES variations were weaker in the 'REG' scenario than in the 'FRANCE' scenario.

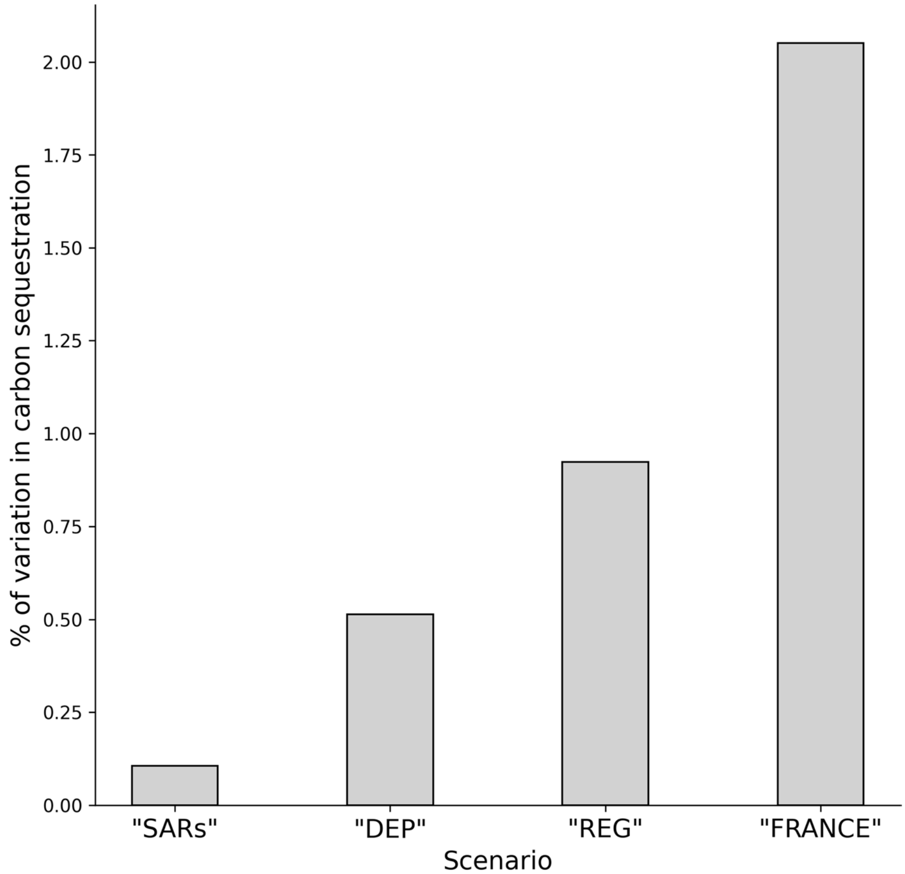

Fig. 2 Increase in carbon sequestration observed at the country scale in each optimisation scenario. The percentages refer to the variation of the optimised configuration of carbon sequestration from the value of the initial configuration. All scenarios optimised carbon sequestration but imposed no-loss constraints to other ecosystem services at different spatial extents, namely in each small agricultural region (SAR) ('SARs' scenario), department, ('DEP' scenario) and administrative region ('REG' scenario) and in all of France ('FRANCE' scenario)

In all administrative regions, for each ES, there were simultaneous increases in some SARs and decreases in others; however, the variations (positive and negative) had different intensities in different administrative regions areas depending on the land use–related constraints and the diversity of land cover. Some SARs, showed an increase in the 'REG' scenario and a decrease in the 'FRANCE' scenario for the same ESs, or vice versa. Among all the ESs, timber growth showed the weakest difference between the 'REG' and 'FRANCE' scenarios due to the constraints imposed on the forest land cover class.

Ecosystem services co-variations

The exploration of correlation among couples of ES variations showed significant results; however, few correlations were strong ($|\rho| \geq 0.5$) (Table 1). Carbon sequestration and crop production exhibited a slight trade-off, which was weaker in the 'SARs' and 'DEP' scenarios than in the 'REG' and 'FRANCE' scenarios. This means that in the 'FRANCE' scenario, the SARs tended to specialise either in carbon sequestration or in crop production, being these two ecosystem services sustained by different land covers. Synergy was observed between carbon sequestration and timber growth. Interestingly, ρ did not increase monotonously with increasing no-loss constraint scales for carbon sequestration and crop production. Rather, it increased until the 'REG' scenario and then decreased for 'FRANCE', suggesting that the strategies implemented to achieve optimisation were different at these scales. Correlations between crop production and timber growth were not intuitive with enlarging scale at which no-loss constraints were imposed: the relation was positive in the 'SARs' scenario, non-significant in the 'DEP' scenario, and finally negative for the 'REG' and 'FRANCE' scenario, showing that, with enlarging scales, these ecosystem services were allocated to different SARs. Correlations involving livestock production were not strong in any scenario.

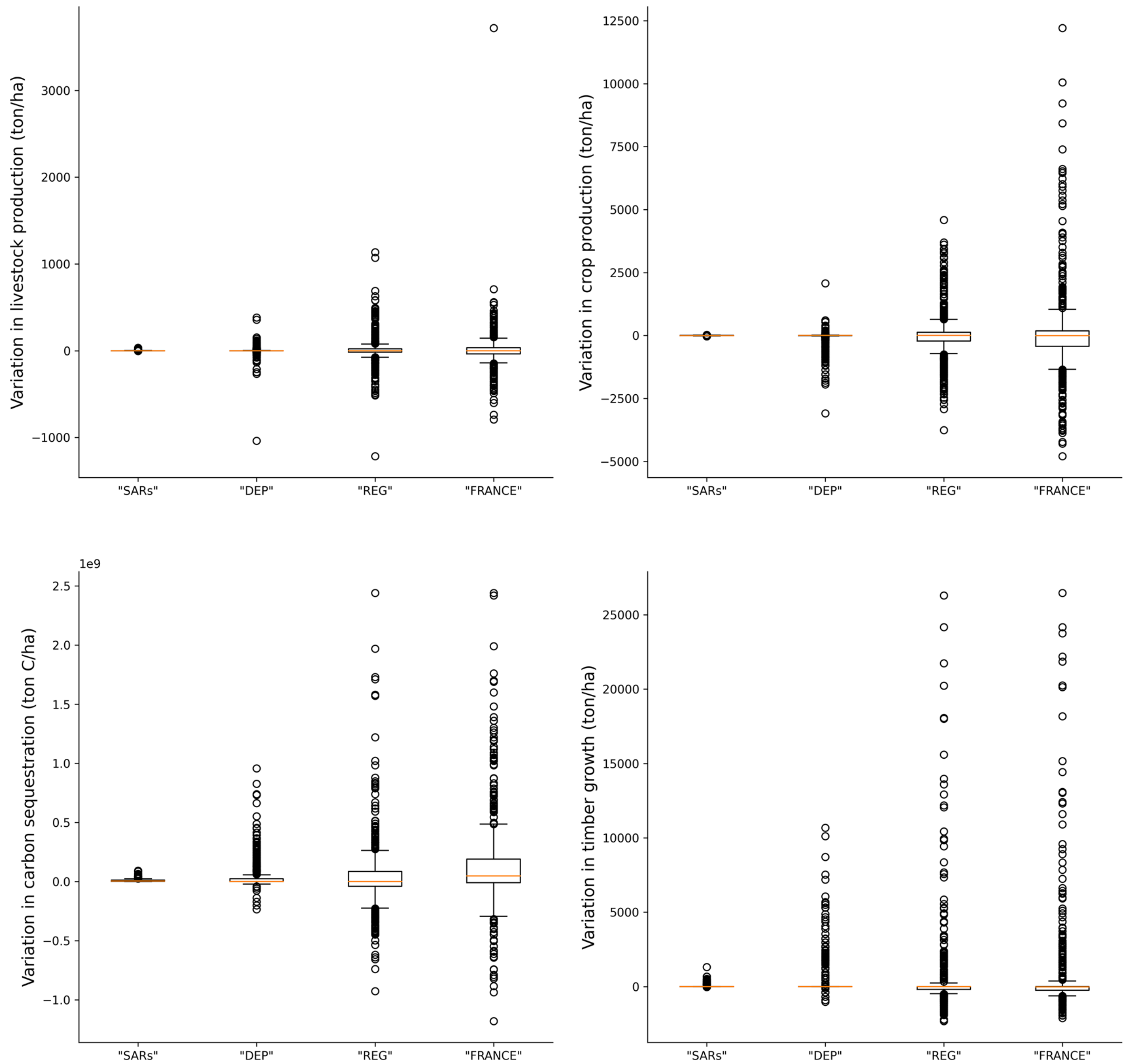

Fig. 3 Boxplots representing the variability of the ecosystem service variations among the small agricultural regions (SARs) for each scenario (n = 709). All scenarios optimised carbon sequestration but imposed no-loss constraints on other ecosystem services at different spatial extents, namely in each small agricultural region (SAR) ('SARs' scenario), department area, ('DEP' scenario) and administrative region area ('REG' scenario) and in all of France ('FRANCE' scenario)

The stronger correlation coefficient was observed between crop production and livestock production in the 'DEP' scenario (negative correlation), but then it is decreased in strength with the 'REG' and 'FRANCE' scenario.

Discussion

We explored the influence of the spatial extent at which strong sustainability is addressed. By optimising one ES (carbon sequestration) in France, we explored the influence of the spatial scale of no-loss constraint imposition on potentially conflicting ESs, thereby exploring ways to conciliate human activities (ES related to the manufactured capital) with the

Fig. 4 Maps of the variation of ecosystem services per hectare in each small agricultural region (SAR) for the 'REG' and 'FRANCE' scenarios. Boundaries of the administrative regions are marked for the 'REG' scenario (left column)

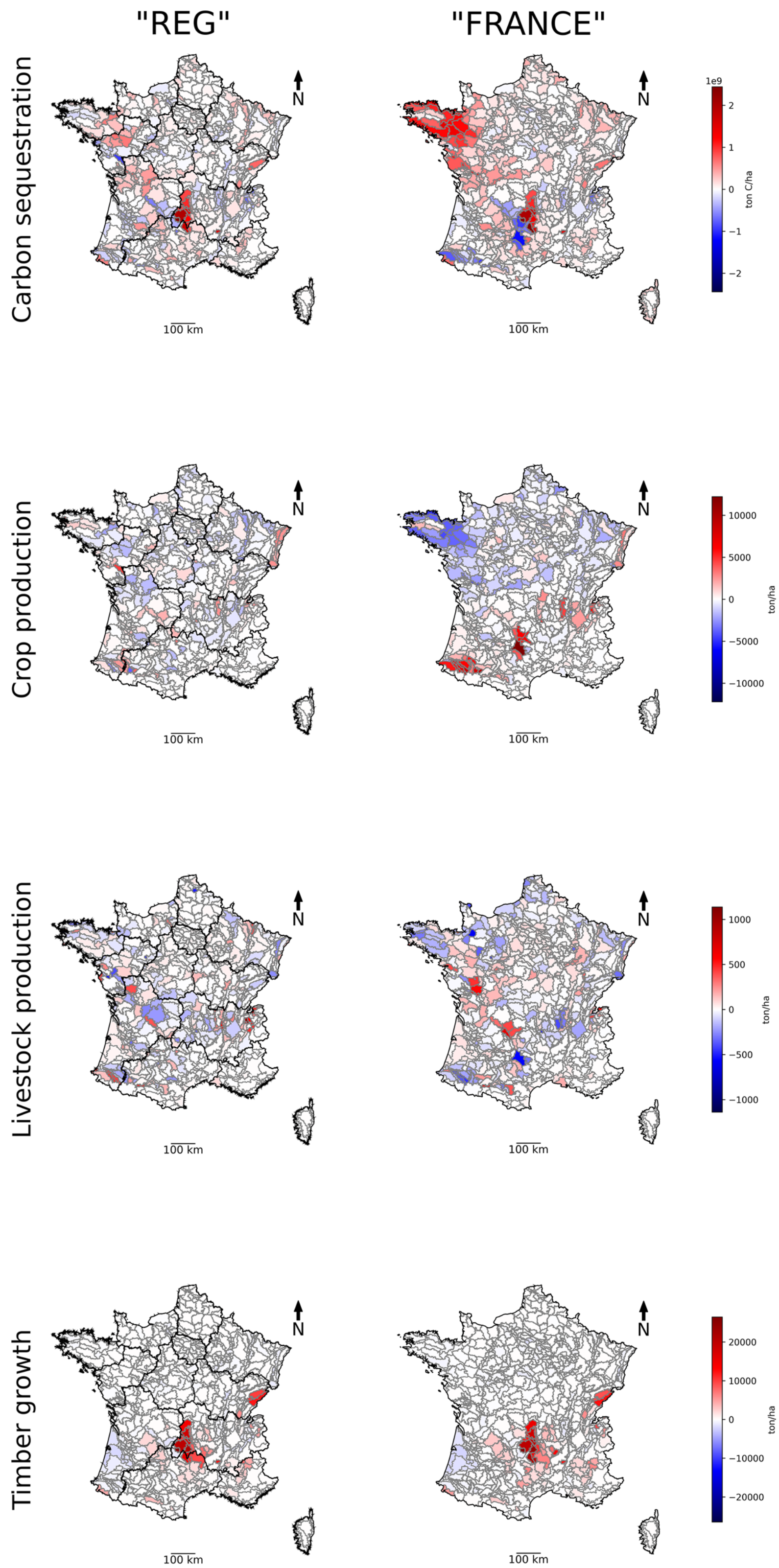

Table 1 Spearman correlation coefficients between coupled variations of ecosystem services in different scenarios

	CP	LP	TG
'SARs' scenario			
CS	−0.48	−0.26	0.21
CP		0.10	0.29
LP			–
'DEP' scenario			
CS	−0.43	−0.12	0.48
CP		−0.37	–
LP			−0.34
'REG' scenario			
CS	−0.68	−0.20	0.62
CP		−0.15	−0.33
LP			−0.36
'FRANCE' scenario			
CS	−0.70	−0.15	0.44
CP		−0.12	−0.23
LP			−0.28

The Spearman correlation coefficient was computed considering the variation of ecosystem services observed in all the small agricultural regions (SARs) after optimisation. All Spearman correlation coefficients were statistically significant ($p < 0.001$), except those marked by '–'

CS carbon sequestration, *CP* crop production, *LP* livestock production, *TG* timber growth, *DEP* department, *REG* administrative region. The name of the scenarios correspond to the spatial extent at which no-loss constraints are posed

natural capital (in this case carbon sequestration). Two main outcomes were gleaned from the results: (1) There is a trade-off related to the choice of spatial scale for no-loss ES management—specifically, implementation at larger scales may cause a greater increase in the target ES but may also increase land cover specialisation and inequalities across spatial units. In contrast, smaller spatial scales tend to promote local multifunctionality of ESs but cause poorer optimisation performance of the target ES. (2) Trade-offs among ESs can differ according to the scale at which the constraints were applied. The differences observed across scales are in line with the many observations made in landscape ecology (Wu 2004; Frazier 2022), and confirm that the considering different scales lead to different results and insights.

Trade-offs at different spatial scales of no-loss constraints

Increasing the spatial extent of the scale at which no-loss constraints are imposed increases the optimisation performance of the targeted ES, which aligns with previous studies. For example, Hölting et al. (2019) found that if the supply of an ES cannot be maximised at one scale, another scale may be able to better address the goal. Pohjanmies et al. (2017) demonstrated, in their multi-objective optimisation, that the conflict between carbon storage and timber extraction is less strict when the optimisation problem is posed at larger spatial scales. However, the better performance achieved with the no-loss constraints at larger scales comes at a cost: in this case, regions tend to be more specialised in certain ESs. Specifically, our results showed that some SARs tend to specialise in crop production and others in carbon sequestration, which is likely to lead to inequalities as some regions may specialise in intensified land uses (Teillard et al. 2017; Shi et al. 2021) with increased use of pesticides and less nature-related land cover (e.g., grassland and forest). In our specific case, the increase in carbon sequestration in certain areas was possibly due to an increase in grassland, which allowed for increased carbon sequestration but removed space for crop and livestock production, though it did so to a lesser extent than cereal cultivation for intensive livestock production. The decrease in nature-related land cover in these regions would also decrease other ESs not considered in our modelling, such as recreation potential (Paracchini et al. 2014), erosion control (García-Nieto et al. 2013) and atmospheric NO_2 removal (Zulian et al. 2014). In contrast, imposing constraints at a smaller scale tends to preserve diversity of land uses locally, softening the inequalities among spatial units. However, this decreases the overall performance of the target ES at the regional scale.

Enhancing ES multifunctionality at different scales requires different strategies. Some studies have pointed out that multifunctionality at one scale can be obtained through either multifunctional smaller-scales spatial units or mono-functional (but different) smaller-scale spatial units (Accatino et al. 2018). The land-sparing and land-sharing debate grew from a need to conciliate biodiversity and agricultural production (Green et al. 2005) but has been extended to conciliation among multiple ESs (Kremen 2015) and scales (Fischer et al. 2014; Accatino et al. 2019). In our study, the 'FRANCE' scenario led to land segregation (see also Teillard et al. 2017) at the national scale corresponding to a land-sparing strategy; conversely, the 'DEP' and 'SARs' scenarios promoted land-sharing in which lower-scale spatial units (SARs or department) tended to promote multiple ESs. The results of the 'FRANCE' scenario corroborate the statement by Wu (2019), according to which strong sustainability achieved at one scale (in this case a country) can be achieved with weak sustainability at smaller scales, where decreases in ESs are observed.

Trade-offs and synergies among ecosystem services by spatial scale

Changing the scale at which no-loss constraints were imposed led to changes in the strength of trade-offs and synergies among ESs, which directly aligns with the considerations of Bennett et al. (2009). These changes in the spatial extent of imposing no-loss constraints also led to changes in the strategies implemented to address optimisation. Crop production and carbon sequestration are conflicting ESs as they are mostly promoted by different land use types (cropland and grassland/forest, respectively) (Shi et al. 2021). When constraints were imposed at the SAR scale, it was difficult to promote the two ESs in the same spatial unit. Moreover, when constraints were imposed at larger spatial extents, SARs tended to specialise in one or the other ES, enhancing the trade-off between them. This corroborates some previous considerations about scaling issues in landscape ecology, i.e., that changes in mechanisms can occur at different scales behind a certain observation (Frazier et al. 2022).

The observed carbon storage and timber growth patterns (increasing synergy strength until the 'REG' scenario, but lower strength in the 'FRANCE' scenario) resulted from the difference in land use types associated with these ESs. When forest was promoted to enhance carbon storage, it synergised with timber growth. In the 'FRANCE' scenario, carbon storage was promoted by an increase in grassland, which created a synergy with livestock production (Accatino et al. 2019) but a trade-off with timber growth. Therefore, a single spatial unit (here, a SAR) can have different fates according to the spatial scale at which no-loss constraints are imposed.

Methodological considerations

In this study, we explicitly linked the tool of "optimization with no-loss" with the concepts of strong sustainability. The idea of optimizing one ES with constraints of no-loss posed on other ESs translated into a mathematical tool the concept of strong sustainability, according to which the improvement of a service provided by a landscape should come with no expense of other ESs (Wu 2019). Therefore, our study can be seen as a multi-scale study of strong sustainability. In addition, provided the availability of data and opportune territorial units, this study can be applied also to other countries or geographical regions and with other ecosystem services optimized. However, because the model is based on data, it is necessary to re-calibrate the parameters if applied to other regions.

The study has some limitations. For example, livestock production could have been more detailed, including different types of production systems, such as grassland-based or crop-livestock systems (see Pinsard et al. (2021) and Pinsard and Accatino (2023) at the SAR scale). However, it provided value for grassland, thus addressing a limitation of our previous study (Shi et al. 2021). Furthermore, more ESs could have been included in the study. We focused on those that were suitable for the statistical model considered, which were based on land cover and provided benefits not strictly linked to the place where they were provided. However, we infer that the inclusion of more ESs would have lowered the performance of the targeted optimised ES. Shi et al. (2021) similarly found that adding more objectives to the optimisation process lowered the performance of the optimised objectives. Although lower performances may have been obtained by adding other ESs, we argue that the relative performance obtained in the different scenarios would not have changed.

Landscape scale as an optimal scale?

In landscape ecology it is important to conduct analyses at multiple scales in order to see how patterns change (Wu 2004; Frazier 2022; Sun et al. 2022). Our multi-scale study highlighted a trade-off related to the scale at which no-loss constraints are posed: at larger spatial scales, the performance of the target optimised ES was improved and spatial inequalities increased. At smaller spatial scales, the performance of the target optimised ES was more modest, but with lower (or null) increase of spatial inequalities. A question arising from this is: *is there an optimal scale at which we can soften trade-offs among ecosystem services and at the same time do not create spatial inequalities?*

Some studies have discussed criteria for setting a preferred spatial scale. More than one study support the landscape scale (which, in this study, can be identified with the SAR or with the department) as pivotal (Wu 2013, 2019; Mastrangelo et al. 2014; Opdam et al. 2018) because this is the scale at which multiple and complex relations among stakeholders and the environment occur. Other studies have highlighted the importance of considering the scales at which decisions are made, which may relate to specific beneficiary stakeholders (Chan et al. 2006; Raudsepp-Hearne and Peterson 2016). However, decisions are often made at multiple scales (Gitay et al. 2005), and optimal scales can differ among ESs. In addition, also trade-offs in decision-making have to be considered (see Zhang et al. 2015). Hence, the contribution of this study lies in highlighting the trade-offs related to the choice of the spatial scale at which no-loss constraints are posted. As in Shi et al. (2021), we argue that addressing smaller spatial scales is optimal as it avoids the local environmental impacts of land-sparing strategies (e.g., the local impact of pesticides; see Geiger et al. 2010). In addition, as Wu (2019) stated, sustainability at larger scales is achieved only if it is achieved at all local scales, therefore, framing sustainability problems at the local scale, with local solutions for softening trade-off would largely be beneficial. A solution more oriented to land-sharing principles, addressing multifunctionality at smaller scales (Schlinder et al. 2014; Pohjanmies et al. 2017), by addressing no-loss strategies at lower spatial scales would lead to lower performance of the ES optimisation at the country scale, though certain efforts could promote practices at the local scale based, for example, on conservation agriculture and ecological intensification (Schipanski et al. 2014; Autret et al. 2016; Stella et al. 2019).

Conclusion

Our study showed that when an ES is optimised with no-loss constraints on other ESs, the spatial scale at which the constraints are imposed matters. In particular, we showed a trade-off. Though larger spatial extents at which no-loss constraints allow for better performance of the targeted ES, they also lead to increased specialisation of landscapes by adopting land-sparing strategies, which may cause social inequalities. In contrast, smaller scales promote and preserve more multifunctional landscapes but allow only modest increases in the target ES. Future research can focus on land cover types that promote multifunctionality at a lower scales (land-sharing strategies) in order to promote local multifunctionality and the optimisation of target ESs. The research of the optimal scale for no-loss ES management can be formalised as an optimisation problem; however, stakeholder involvement and their requirements should also be considered.

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Declarations

Competing interests The authors declare no competing interests.

References

Accatino F, Creed IF, Weber M (2018) Landscape consequences of aggregation rules for functional equivalence in compensatory mitigation programs. Conserv Biol 32:694–705

Accatino F, Tonda A, Dross C, Léger F, Tichit M (2019) Trade-offs and synergies between livestock production and other ecosystem services. Agric Syst 168:58–72

Anderson CR, Moore SK, Tomlinson MC, Silke J, Cusack CK (2015) Living with harmful algal blooms in a changing world: strategies for modeling and mitigating their effects in coastal marine ecosystems. Coastal and marine hazards, risks, and disasters. Elsevier, Amsterdam, pp 495–561

Autret B, Mary B, Chenu C, Balabane M, Girardin C, Bertrand M, Grandeau G, Beaudoin N (2016) Alternative arable cropping systems: a key to increase soil organic carbon storage? Results from a 16 year field experiment. Agric Ecosyst Environ 232:150–164

Bar Massada A, Radeloff VC (2010) Two multi-scale contextual approaches for mapping spatial pattern. Landsc Ecol 25:711–725

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12:1394–1404

Bouwma I, Schleyer C, Primmer E, Winkler KJ, Berry P, Young J, Carmen E, Špulerová J, Bezák P, Preda E, Vadineanu A (2018) Adoption of the ecosystem services concept in EU policies. Ecosyst Serv 29:213–222

Butsic V, Kuemmerle T (2015) Using optimization methods to align food production and biodiversity conservation beyond land sharing and land sparing. Ecol Appl 25:589–595

Chan KMA, Shaw MR, Cameron DR, Underwood EC, Daily GC (2006) Conservation planning for ecosystem services. PLoS Biol 4:e379

Ericksen PJ, Ingram JS, Liverman DM (2009) Food security and global environmental change: emerging challenges. Environ Sci Policy 12: 373–377 https://doi.org/10.1016/j.envsci.2009.04.007

Fischer J, Abson DJ, Butsic V, Chapperll M, Ekroos J, Hanspach J, Kuemmerle T, Smith HG, von Wehrden H (2014) Land sparing versus land sharing: moving forward. Conserv Lett 7:149–157

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connel C, Ray DK, West PC, Belzer C (2011) Solutions for a cultivated planet. Nature 478:337–342

Frazier AE (2022) Scope and its role in advancing a science of scaling in landscape ecology. Landsc Ecol 23:1–7

García-Nieto AP, García-Llorente M, Iniesta-Arandia I, Martín-López B (2013) Mapping forest ecosystem services: from providing units to beneficiaries. Ecosyst Serv 4:126–138

Geiger F, Bengtsson J, Berendse F, Weisser WW, Emmerson M, Morales MB, Ceryngier P, Liira, J, Tscharntke T, Winqvist C, Eggers S, Bommarco R, Pärt T, Bretagnolle V, Plantegenest M, Clement LW, Dennis C, Palmer C, Oñate JJ, Guerrero I, Hawro V, Aavik T, Thies C, Flohre A, Hänke S, Fischer C, Goedhart PW, Inchausti P (2010) Persistent negative effects of pesticide on biodiversity and biological control potential on European farmland. Basic Appl Ecol 11:97–105

Gitay H, Blanco H, Biggs R (2005) Assessment process. Ecosyst Hum Well-Being 119

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty K, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Grêt-Regamey A, Weibel B, Bagstad KJ, Ferrari M, Geneletti D, Klug H, Schirpke E, Tappeiner U (2014) On the effects of scale for ecosystem services mapping. PLoS ONE 9:e112601

Groot JC, Rossing WA (2011) Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. Methods Ecol Evol 2:643–650

Groot JC, Oomen GJ, Rossing WA (2012) Multi-objective optimization and design of farming systems. Agric Syst 110:63–77

Hölting L, Jacobs S, Felipe-Lucia MR, Maes J, Noström AV, Plieninger T, Cord AF (2019) Measuring ecosystem multifunctionality across scales. Environ Res Lett 14:124083

Jopke C, Kreyling J, Maes J, Koellner T (2015) Interactions among ecosystem services across Europe: bagplots and cumulative correlation coefficients reveal synergies, trade-offs, and regional patterns. Ecol Indic 49:46–52

Kon Kam King J, Granjou C, Fournil J, Cecillon L (2018) Soil sciences and the French 4 per 1000 Initiative: the promises of underground carbon. Energy Res Soc Sci 45:144–152

Kremen C (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. Ann N Y Acad Sci 1355:52–76. https://doi.org/10.1111/nyas.12845

Lindborg R, Gordon LJ, Malinga R, Bengtsson J, Peterson G, Bommarco R, Deutch L, Gren Å, Rundlöf M, Smith HG (2017) How spatial scale shapes the generation and management of multiple ecosystem services. Ecosphere 8:e01741

Liu Z, Zhou Q, Ma Q, Kuang W, Daryanto S, Wang L, Wu J, Liu B, Zhu J, Cao C, Li X (2023) Scale effect of climate factors on soil organic carbon stock in natural grasslands of northern China. Ecol Indic 146:109757

Ma Q, Wu J, He C, Hu G (2019) Reprint of "Spatial scaling of urban impervious surfaces across evolving landscapes: from cities to urban regions." Landsc Urban Plan 187:132–144

Mastrangelo ME, Weyland F, Villarino SH, Barral MP, Nahuelhual L, Laterra P (2014) Concepts and methods for landscape multifunctionality and a unifying framework based on ecosystem services. Landsc Ecol 29:345–358

MEA (2005) Ecosystems and human well-being: wetlands and water synthesis

Metzger MJ, Rounsevell M, Acosta-Michlik L, Leemans R, Schröter D (2006) The vulnerability of ecosystem services to land use change. Agric Ecosyst Environ 114:69–85

Moindjié IA, Pinsard C, Accatino F, Chakir R (2022) Interactions between ecosystem services and land use in France: a spatial statistical analysis. Front Environ Sci 10:954655

Mouchet M, Paracchini M, Schulp C, Stürck J, Verkerk PJ, Verburg PH, Lavorel S (2017) Bundles of ecosystem (dis) services and multifunctionality across European landscapes. Ecol Indic 73:23–28

Musacchio L (2013) Key concepts and research priorities for landscape sustainability. Landsc Ecol 28:995–998

Nelson E, Mendoza G, Regetz J, Polansky S, Tallis H, Cameron D, Chan KM, Daily GC, Goldstein J, Kareiva PM, Londsdorf E (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front Ecol Environ 7:4–11

Opdam P, Luque S, Nassauer J, Verburg PH, Wu J (2018) How can landscape ecology contribute to sustainability science? Landsc Ecol 33:1–7

Paracchini ML, Zulian G, Kopperoinen L, Maes J, Schägner JP, Termansen M, Zandersen M, Perez-Soba M, Scholefield PA, Bidoglio G (2014) Mapping cultural ecosystem services: a framework to assess the potential for outdoor recreation across the EU. Ecol Indic 45:371–385
Pinsard C, Accatino F (2023) European agriculture's robustness to input supply declines: a French case study. Environ Sustain Indicat 17:100219. https://doi.org/10.1016/j.indic.2022.100219
Pinsard C, Martin S, Léger F, Accatino F (2021) Robustness to import declines of three types of European farming systems assessed with a dynamic nitrogen flow model. Agric Syst 193:103215
Pohjanmies T, Eyvindson K, Triviño M, Mönkkönen M (2017) More is more? Forest management allocation at different spatial scales to mitigate conflicts between ecosystem services. Landsc Ecol 32:2337–2349
Potschin M, Haines-Young R (2013) Landscape, sustainability and the place-based analysis of ecosystem services. Landsc Ecol 28:1053–1065
Qiu S, Yue W, Zhang H, Qi J (2017) Island ecosystem services value, land-use change, and the National New Area Policy in Zhoushan Archipelago, China. Isl Stud J 12:177–198
Raudsepp-Hearne C, Peterson GD (2016) Scale and ecosystem services: how do observation, management, and analysis shift with scale: lessons from Québec. Ecol Soc 21:16
Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc Natl Acad Sci 107:5242–5247
Rodríguez JP, Beard TD Jr, Bennett EM, Cumming GS, Cork SJ, Agard J, Dobson AP, Peterson GD (2006) Trade-offs across space, time, and ecosystem services. Ecol Soc. https://doi.org/10.5751/ES-01667-110128
Ruijs A, Wossink A, Kortelainen M, Alkemade R, Schulp CJE (2013) Trade-off analysis of ecosystem services in Eastern Europe. Ecosyst Serv 4:82–94
Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K, Kaye JP, Kemanian AR, Mortensen DA, Ryan MR, Tooker J, White C (2014) A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric Syst 125:12–22
Schlinder S, Sebasvari Z, Damm C, Euller K, Mauerhofer V, Schneidergruber A, Biró M, Essl F, Kanka R, Lauwaars SG, Schulz-Zunkel C (2014) Multifunctionality of foodplain landscapes: relating management options to ecosystem services. Landsc Ecol 29:229–244
Scholes RJ, Reyers B, Biggs R, Spierenburg MJ, Buriappah A (2013) Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. Curr Opin Environ Sustain 5:16–25
Seppelt R, Lautenbach S, Volk M (2013) Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales. Curr Opin Environ Sustain 5:458–463
Shi Y, Pinsard C, Accatino F (2021) Land sharing strategies for addressing the trade-off between carbon storage and crop production in France. Reg Environ Change 21:1–14
Stella T, Mouratiandou I, Gaiser T, Berg-Mohnicke M, Wallor E, Ewert F, Nandel C (2019) Estimating the contribution of crop residues to soil organic carbon conservation. Environ Res Lett 14:094008. https://doi.org/10.1088/1748-9326/ab395c
Stürck J, Verburg PH (2017) Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. Landsc Ecol 32:481–500
Sun X, Ma Q, Fang G (2022) Spatial scaling of land use/land cover and ecosystem services across urban hierarchical levels: patterns and relationships. Landsc Ecol 31:1–25
Tallis H, Polasky S (2011) Assessing multiple ecosystem services: an integrated tool for the real world. Natural capital: theory and practice of mapping ecosystem services. Oxford University Press, Oxford, pp 34–50
Teillard F, Doyen L, Dross C, Jiguet F, Tichit M (2017) Optimal allocations of agricultural intensity reveal win-no loss solutions for food production and biodiversity. Reg Environ Change 17:1397–1408. https://doi.org/10.1007/s10113-016-0947-x
Wu J (2004) Effects of changing scale on landscape pattern analysis: scaling relations. Landsc Ecol 19:125–138
Wu J (2013) Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc Ecol 28:999–1023
Wu J (2019) Linking landscape, land system and design approaches to achieve sustainability. J Land Use Sci 14:173–189
Zhang L, Fu B, Lü Y, Zeng Y (2015) Balancing multiple ecosystem services in conservation priority setting. Landsc Ecol 30:535–546
Zulian G, Polce C, Maes J (2014) ESTIMAP: a GIS-based model to map ecosystem services in the European Union. Ann Bot 4:1–7