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

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Handling ecosystem service trade-offs in France: the importance of the level 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 level at which no-loss constraints are imposed is relevant.

Objectives We examined the influence of the spatial level of constraints on ESs when one ES was optimised. Specifically, we investigated how carbon sequestration could be maximized at different spatial levels in France with constraints of no-loss on other ES.

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 level in different scenarios – 'SARs', 'NUTS3', 'NUTS2' and 'FRANCE' – whose names correspond to the spatial level at which no-loss constraints were imposed. We analysed differences between optimized and initial configurations.

Results Optimized CS at the country scale increased with the spatial level (~+0.51% for 'NUTS3' and ~+2.05% for 'FRANCE'). The variability of ES variation among the SARs similarly increased. This suggested that constraints at larger levels lead to ES segregation. Correlations among ES variations varied with the scenarios (Spearman's ρ between CS and CP was −.43 for 'NUTS3' and −.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 levels promoted higher performance of the target ES but also spatial inequality. We argue that addressing smaller levels will lead to land-sharing solutions that avoid the local environmental impacts of land-sparing strategies.

Keywords: Optimization, multi-functionality, multi-level, land use strategy

1 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). Some examples of this are evident in public policies, such as the Biodiversity Strategy of the European Commission (2020), and spontaneous initiatives, such as the '4 per 1000' initiative (Kon Kam King et al. 2018), which encourages stakeholders to find solutions for progressive carbon storage in soils. However, a challenge has arisen in conciliating provisioning services (e.g., agricultural and timber production, timber extraction) with regulating services (e.g., carbon sequestration). 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).

Trade-offs impede conciliation between different ESs (Bennett et al. 2009), especially between those of 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). Avoiding or softening these trade-offs would promote multifunctionality of land, including its capacity to provide multiple ES simultaneously (Hölting et al. 2019) and/or win-no-loss solutions in which one ES can be increased without reducing others (Teillard et al. 2017). As such, many studies have highlighted the importance of simultaneously maintaining the provision of several different ESs (e.g., Rodríguez et al. 2006; Stürck and Verburg 2017).

The spatial scales or levels at which ES trade-offs and multifunctionality are studied have received recent attention. In the literature, spatial 'scale' and 'level' are terms often used interchangeably (Ewert et al. 2006, Mastrangelo et al. 2014, Stürck and Verburg 2017), but according to Ewert et al. (2006), 'scale' refers to a physical dimension, whereas 'level' refers to an organisational level of a hierarchical system. Thus, although both terms have a spatial connotation, 'level' may be associated with particular stakeholders, levels of administration, and decision-making. Some research has noted that studies of ES trade-offs often choose scales and levels 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 or level 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 or levels 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 or level at which ESs are most effectively managed (Mastrangelo et al. 2014).
Scale issues have so far been addressed and discussed in mapping (Grêt-Regamey et al. 2014), modelling (Qiu et al. 2017) and multifunctionality measurement (Stürck and Verburg 2017). 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 land use multifunctionality and no-loss ES optimisation at the regional scale can be achieved by management at different spatial levels, which produce different results. In other words, a region (here, country) represents a hierarchical system formed by territorial units and subunits, so the pursuit of no-loss ES management can target both the national level and the levels of each unit and subunit. This research therefore aimed to address the following questions: How does the spatial level at which no-loss constraints are imposed influence the achievement of no-loss ES management at the regional scale? And are trade-offs and synergies among ESs softened or enhanced at different spatial levels? Modelling can help to address these questions as it allows for 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 level at which ES no-loss constraints are imposed to obtain no-loss ES management strategies at the regional scale (here, France). More precisely, we aimed at maximising carbon sequestration in France using a model that imposes no-loss constraints on other ESs at different spatial levels (i.e., small agricultural region [SAR], Nomenclature of Territorial Units for Statistics [NUTS]3, NUTS2, country). Following Ewert et al. (2006), we use 'scale' to refer to the scale at which the optimisation should occur (i.e., the regional scale) and 'level' for the territorial units and subunits. SARs, NUTS3, NUTS2,

and France are spatial entities associated with specific organisational levels, stakeholders and decision-makers. 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 level considered and investigated the consequences for the other ESs within the spatial units. A similar multi-level optimization analysis was done by Pohjanmies et al. (2017) involving the multi-criteria optimization of timber extraction and carbon storage, at the level 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 level. 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 level to address.

2 MATERIALS AND METHODS

2.1 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} yr^{-1}) and fodder land θ_{PFOD} (€ ha^{-1} yr^{-1}), average crop energy content θ_E (Mcal ha^{-1}) and climatic variables, namely rainfall θ_R (mm yr^{-1}) and temperature θ_T (ºC). 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:

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

Eq. (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 ESs 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).

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

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

2.2 Optimisation scenarios

Optimisation begins from an initial configuration of variables. Some variables are chosen as 'driving variables' (Accatino et al. 2019) and systematically changed to optimise the output based on 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 level at which no-loss constraints are imposed influence the achievement of no-loss ES management at the regional scale?* We performed mono-objective (i.e., carbon sequestration) optimisation with no-loss constraints on other objectives (i.e., ESs). In each scenario, the objective was maximised for all of France and no-loss constraints were imposed at different spatial levels: other ESs were forced not to decrease and pesticide expenses were forced not to increase. This optimisation is defined with:

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

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 ('NUTS3'), Ω_h represents each metropolitan French department; in the third scenario ('NUTS2'), Ω_h represents each metropolitan French administrative region; 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 level on our optimisation exercise. First, we observed the total increase in carbon storage at the country level. 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 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 ρ <−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).

Fig. 1 Boundaries of the spatial units at which no-loss constraints were applied to the considered ecosystem services (carbon sequestration, crop production, livestock production, timber growth) as carbon sequestration was maximised at the country scale. From left to right, the boundaries correspond to small agricultural regions (SARs), NUTS3, NUTS2 and France. In light gray, the SARs boundaries (the spatial resolution of the model) are provided for the 'NUTS3', 'NUTS2' and 'FRANCE' scenarios.

3 Results

3.1 Changes in ecosystem services

The results show that no-loss constraints imposed at larger spatial levels allow 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 'NUTS3', 'NUTS2' and 'FRANCE' scenarios, with the latter obtaining the best performance.

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 corresponding to 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), NUTS3 area, ('NUTS3' scenario) and NUTS2 area ('NUTS2' scenario) and in all of France ('FRANCE' scenario).

The variability of the ES variations observed among the SARs increased with the spatial level 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 level). The 'NUTS3' scenario showed weak variability with some negative variations at the SAR level. High variability was observed in the 'NUTS2' 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.

Fig. 3 Boxplots representing the variability of the ecosystem service variations among the small agricultural regions (SARs) for each scenario. All scenarios optimised carbon sequestration but imposed no-loss constraints on other ecosystem services at different spatial extents, namely in each SAR ('SARs' scenario), NUTS3 area, (‘NUTS3’ scenario) and NUTS2 area (‘NUTS2’ scenario) and for all of France (‘FRANCE’ scenario).

We mapped the results for the ‘NUTS2’ and ‘FRANCE’ scenarios with the same colour scale for each ES (Fig. 4); SAR-level variations in the ‘SARs’ and ‘NUTS3’ scenarios were too weak to be observed with the same colour scale. There are evident differences between the ‘NUTS2’ and the ‘FRANCE’ scenarios. In the ‘FRANCE’ scenario, the NUTS2 administrative regions have high levels 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 northeast of France (Brittany), where carbon sequestration increased in all the SARs as crop and animal production decreased. This 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. Other groups of SARs presented opposite specialisation, such as in the centre of France and the Pyrenees. ES variations were weaker in the ‘NUTS2’ scenario than in the ‘FRANCE’ scenario. In all NUTS2 areas, 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 NUTS2 areas depending on the land use–related constraints and the diversity of land cover. Some SARs, showed an increase in the ‘NUTS2’ scenario and a decrease in the ‘FRANCE’ scenario for the same ESs, or vice versa. Among all the ESs, timber growth showed the lowest difference between the ‘NUTS2’ and ‘FRANCE’ scenarios due to the constraints imposed on the forest land cover class.

Fig. 4 Maps of the variation of ecosystem services per hectare in each small agricultural region (SAR) for the ‘NUTS2’ and ‘FRANCE’ scenarios. Boundaries of the NUTS2 regions are marked for the ‘NUTS2’ scenario (left column).

3.2 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 ‘NUTS3’ scenarios than in the ‘NUTS2’ and ‘FRANCE’ scenarios. Synergy was observed between carbon sequestration and timber growth. Interestingly, ρ did not increase monotonously with increasing no-loss constraint levels for carbon sequestration and crop production. Rather, it increased until the 'NUTS2' scenario and then decreased for 'FRANCE', suggesting that the strategies implemented to achieve optimisation were different at these scales.

Table 1. Spearman correlation coefficients between coupled variations of ecosystem services in different scenarios. The 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 '-'. Legend: CS, carbon sequestration; CP, crop production; LP, livestock production; TG, timber growth.

'SARs' scenario			
	CP	LP	TG
CS	−.48	−.26	.21
CP		.10	.29
LP			-
'NUTS3' scenario			
	CP	LP	TG
CS	−.43	−.12	.48
CP		−.37	-
LP			−.34
'NUTS2' scenario			
	CP	LP	TG
CS	−.68	−.20	.62
CP		−.15	−.33
LP			−.36
'FRANCE' scenario			
	CP	LP	TG
CS	−.70	−.15	.44
CP		−.12	−.23
LP			−.28

4 DISCUSSION

By optimising one ES (carbon sequestration) at the regional scale, we explored the influence of the spatial level of no-loss constraint imposition on potentially conflicting ESs. Two main outcomes were gleaned from the results: 1) There is a trade-off related to the choice of spatial level for no-loss ES management – specifically, implementation at larger levels may cause a greater increase in the target ES but may also increase land cover specialisation and inequalities in the spatial units. In contrast, smaller spatial levels 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 level at which the constraints were applied.

4.1 Trade-offs at different spatial levels of no-loss constraints

Increasing the spatial extent of the level 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 level, another level may be able to better address the goal. Pohjanmies et al. (2017) demonstrated, in their multi-objective optimisation, that the conflict among carbon storage and timber extraction is less strict when the optimisation problem is posed at larger spatial levels. However, the better performance achieved with the no-loss constraints at larger levels comes at a cost: in this case, regions tend to be more specialised in certain ES subsets. Specifically, our study shows 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). This 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 level 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 levels requires different strategies. Some studies have pointed out that multifunctionality at one level can be obtained through either multifunctionality at smaller scales or mono-functional (but different) smaller-level 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

‘NUTS3’ and ‘SARs’ scenarios promoted land-sharing in which lower-level spatial units (SARs or NUTS3) tended to promote multiple ESs.

4.2 Trade-offs and synergies among ecosystem services by spatial level

Changing the level 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 findings 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 level, it was difficult to promote the 2 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.

The observed carbon storage and timber growth patterns (increasing synergy strength until the ‘NUTS2’ 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 most 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, an SAR) can have different fates according to the spatial level at which no-loss constraints are imposed.

4.3 Limits of the study

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) at the SAR level). 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 performances 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.

4.4 Towards an optimal scale

Despite the model's limitations, this study highlighted the trade-offs related to the spatial level at which no-loss constraints are imposed in an optimisation model. At higher spatial levels, the performance of the target optimised ES was improved and spatial inequalities decreased. The next research question addressed by this study was: *are trade-offs and synergies among ESs softened or enhanced at different spatial levels?*

Some studies have discussed criteria for setting a preferred spatial level. Mastrangelo et al. (2014) highlighted the preference for the landscape level for enhancing multifunctionality, as this is the level at which multiple and complex relations among stakeholders and land cover and land use types become evident. 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 levels (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 level. As in Shi et al. (2021), we argue that addressing smaller spatial levels 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). A solution more oriented to land-sharing principles, addressing multifunctionality at smaller levels (Schlinder et al., 2014; Pohjanmies et al., 2017), by addressing no-loss strategies at lower spatial levels would lead to lower performance of the ES optimisation at the country scale, though certain efforts could promote practices at the local level based on conservation agriculture and ecological intensification, for example (Schipanski et al. 2014; Autret et al. 2016; Stella et al. 2019)

5 CONCLUSION

Our study showed that when an ES is optimised with no-loss constraints on other ESs, the spatial level at which the constraints are imposed matters. Though larger spatial extents 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 scale (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.

6 Contribution statement

FA conceived and designed the study, interpreted the results, and led the text writing. YS and AT performed the analysis, produced results, and contributed to text improvement.

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