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1 Handling ecosystem service trade-offs in France: the importance of the
2 level at which no-loss constraints are posed

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47 **Abstract**

48 *Context* Managing land use to promote an ecosystem service (ES) without reducing others is
49 challenging. The spatial level at which no-loss constraints are imposed is relevant.

50

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

54

55 *Methods* We used a statistical model linking land use and land cover variables to ESs (carbon
56 sequestration [CS], crop production [CP], livestock production, timber growth) in French small
57 agricultural regions (SARs). We optimised CS at the country level in different scenarios – ‘SARs’,
58 ‘NUTS3’, ‘NUTS2’ and ‘FRANCE’ – whose names correspond to the spatial level at which no-loss
59 constraints were imposed. We analysed differences between optimized and initial configurations.

60

61 *Results* Optimized CS at the country scale increased with the spatial level ($\sim+0.51\%$ for ‘NUTS3’ and
62 $\sim+2.05\%$ for ‘FRANCE’). The variability of ES variation among the SARs similarly increased. This
63 suggested that constraints at larger levels lead to ES segregation. Correlations among ES variations
64 varied with the scenarios (Spearman’s ρ between CS and CP was -0.43 for ‘NUTS3’ and -0.70 for
65 ‘FRANCE’). This indicated that different land use strategies produce different degrees of
66 enhancement/softening of ES trade-offs/synergies.

67

68 *Conclusions* A trade-off was highlighted: larger levels promoted higher performance of the target ES
69 but also spatial inequality. We argue that addressing smaller levels will lead to land-sharing solutions
70 that avoid the local environmental impacts of land-sparing strategies.

71

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

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82 **1 INTRODUCTION**

83 Ecosystem services (ESs) are increasingly considered in policy and decision-making (Bouwma
84 et al. 2018) as advised by scientists, such as in the Millennium Ecosystem Assessment (MEA
85 2005). Some examples of this are evident in public policies, such as the Biodiversity Strategy
86 of the European Commission (2020), and spontaneous initiatives, such as the ‘4 per 1000’
87 initiative (Kon Kam King et al. 2018), which encourages stakeholders to find solutions for
88 progressive carbon storage in soils. However, a challenge has arisen in conciliating
89 provisioning services (e.g., agricultural and timber production, timber extraction) with
90 regulating services (e.g., carbon sequestration). Increasing agricultural production to meet
91 increasing food demand, for instance, should not harm the provision of other ESs (Ericksen et
92 al. 2009; Godfray et al. 2010; Foley et al. 2011).

93 Trade-offs impede conciliation between different ESs (Bennett et al. 2009), especially between
94 those of provisioning and regulating. A trade-off occurs when the increase in the provision of
95 one ES has negative consequences for another ES (Rodríguez et al. 2006). Many trade-offs are
96 linked to land cover changes (Ruijs et al. 2013) because each land cover type provides a certain
97 set of ESs; land is a scarce resource, so the expansion of one land cover type usually results in
98 a reduction of a competing land cover type and its associated ESs (Metzger et al. 2006).
99 Avoiding or softening these trade-offs would promote multifunctionality of land, including its
100 capacity to provide multiple ES simultaneously (Hölting et al. 2019) and/or win-no-loss
101 solutions in which one ES can be increased without reducing others (Teillard et al. 2017). As
102 such, many studies have highlighted the importance of simultaneously maintaining the
103 provision of several different ESs (e.g., Rodríguez et al. 2006; Stürck and Verburg 2017).

104 The spatial scales or levels at which ES trade-offs and multifunctionality are studied have
105 received recent attention. In the literature, spatial ‘scale’ and ‘level’ are terms often used
106 interchangeably (Ewert et al. 2006, Mastrangelo et al. 2014, Stürck and Verburg 2017), but
107 according to Ewert et al. (2006), ‘scale’ refers to a physical dimension, whereas ‘level’ refers
108 to an organisational level of a hierarchical system. Thus, although both terms have a spatial
109 connotation, ‘level’ may be associated with particular stakeholders, levels of administration,
110 and decision-making. Some research has noted that studies of ES trade-offs often choose scales
111 and levels arbitrarily, failing to sufficiently consider scale-related issues (Mastrangelo et al.
112 2014; Lindborg et al. 2017; Stürck and Verburg 2017). Furthermore, considering only one
113 scale or level often leads to incomplete or even distorted conclusions (Raudsepp-Hearne and
114 Peterson 2016). For these reasons, studies are increasingly advocating for assessments to
115 consider multiple scales or levels at once (Scholes et al. 2013; Anderson et al. 2015; Qiu et al.

116 2017; Raudsepp-Hearne and Peterson 2016; Hölting et al. 2019), ultimately raising the question
117 of the scale or level at which ESs are most effectively managed (Mastrangelo et al. 2014).
118 Scale issues have so far been addressed and discussed in mapping (Grêt-Regamey et al. 2014),
119 modelling (Qiu et al. 2017) and multifunctionality measurement (Stürck and Verburg 2017).
120 In particular, Qiu et al. (2017) modelled ES provision in future scenarios and quantified the
121 trade-offs among ESs at different scales within a watershed in Wisconsin. Their results show
122 that relationships among some of the ESs were consistent across scales, but others had scale-
123 dependent relationships. Stürck and Verburg (2017) tested a set of ES multifunctionality
124 indicators at various scales and concluded that no one indicator was more accurate than the
125 others but further noted that considering indicators at different scales could affect the results
126 and implications.

127 This study aimed to address an additional issue. We hypothesised that land use
128 multifunctionality and no-loss ES optimisation at the regional scale can be achieved by
129 management at different spatial levels, which produce different results. In other words, a region
130 (here, country) represents a hierarchical system formed by territorial units and subunits, so the
131 pursuit of no-loss ES management can target both the national level and the levels of each unit
132 and subunit. This research therefore aimed to address the following questions: How does the
133 spatial level at which no-loss constraints are imposed influence the achievement of no-loss ES
134 management at the regional scale? And are trade-offs and synergies among ESs softened or
135 enhanced at different spatial levels? Modelling can help to address these questions as it allows
136 for linking ES drivers (e.g., land use) to ES outputs (Nelson et al. 2009; Tallis and Polasky
137 2011). Furthermore, coupling modelling with optimisation methods can produce a combination
138 of drivers that maximises a target ES (objective) under certain constraints (Seppelt et al. 2013;
139 Accatino et al. 2019). Optimisation strategies that have been applied to models in the ES
140 literature include mono-objective optimisation with constraints on other objectives (Butsic and
141 Kuemmerle 2015; Accatino et al. 2019) and multi-objective optimisation (Groot et al. 2012;
142 Teillard et al. 2017; Shi et al. 2021).

143 We investigated the effect of the spatial level at which ES no-loss constraints are imposed to
144 obtain no-loss ES management strategies at the regional scale (here, France). More precisely,
145 we aimed at maximising carbon sequestration in France using a model that imposes no-loss
146 constraints on other ESs at different spatial levels (i.e., small agricultural region [SAR],
147 Nomenclature of Territorial Units for Statistics [NUTS]3, NUTS2, country). Following Ewert
148 et al. (2006), we use ‘scale’ to refer to the scale at which the optimisation should occur (i.e.,
149 the regional scale) and ‘level’ for the territorial units and subunits. SARs, NUTS3, NUTS2,

150 and France are spatial entities associated with specific organisational levels, stakeholders and
151 decision-makers. We analysed the extent to which carbon sequestration could be optimised for
152 all of France by imposing constraints on the other ESs at each spatial level considered and
153 investigated the consequences for the other ESs within the spatial units. A similar multi-level
154 optimization analysis was done by Pohjanmies et al. (2017) involving the multi-criteria
155 optimization of timber extraction and carbon storage, at the level of small holding, large
156 holding, and watershed, and region. We also examined the correlations among the variations
157 of ESs to investigate how the intensities of trade-offs and synergies among them varied at each
158 spatial level. We used a model previously defined and parameterised in the literature (Accatino
159 et al. 2019), which links land cover, land use and climatic variables to ES provision. Insights
160 from the present study highlight the consequences of seeking win/no-loss solutions at certain
161 spatial scales and suggest considerations for future studies seeking the optimal spatial level to
162 address.

163 **2 MATERIALS AND METHODS**

164 **2.1 Model description**

165 We adopted the model developed by Accatino et al. (2019) for this study, which is briefly re-
166 described here. Metropolitan France is divided into 714 SARs – territorial units characterised
167 by homogeneous agronomic and pedological conditions. Their boundaries are coincident with
168 the departmental (NUTS3) and regional (NUTS2) boundaries, i.e., a SAR does not intersect
169 multiple departments or regions and may share part of the boundary. For this study, a
170 management area S (ha) was defined for each SAR and divided into land use fractions ϕ_l with
171 $l \in \{C, FOD, TG, PG, F\}$, corresponding to cropland, fodder land, temporary grassland,
172 permanent grassland and forest, respectively. Each land use fraction was in the range 0–1, and
173 the sum of all fractions for each SAR was 1. The management areas could be smaller than the
174 actual surface of a SAR because some land cover types were not considered in the model.
175 Cropland and fodder land represent the annual crops cultivated for human and animal
176 consumption, respectively and temporary grassland is cultivated with harvested grass.
177 Permanent grassland and forest were further divided into subcategories $\varphi_{i,l} \in \Gamma_l$, where Γ_l is the
178 set of sub-fractions of land cover type l . Following the Corine Land Cover (CLC) classification
179 (EEA 2013), permanent grassland was divided into *Pasture* (CLC 231) and *Natural Grassland*
180 (CLC 321) and forest was divided into *Broad Leaved Forest* (CLC 311), *Coniferous Forest*
181 (CLC 312), *Mixed Forest* (CLC 313), *Sclerophyllous Vegetation* (CLC 323) and *Transitional*

182 *Woodland/Shrub* (CLC 324). Cropland, fodder land and temporary grassland had only one
 183 sub-fraction each, equal to 1.

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

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

192

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

193

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

199

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

200

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

203

204 **2.2 Optimisation scenarios**

205 Optimisation begins from an initial configuration of variables. Some variables are chosen as
 206 ‘driving variables’ (Accatino et al. 2019) and systematically changed to optimise the output
 207 based on the imposed constraints until an optimised configuration is reached. In our study, the
 208 initial configuration of variables in the SARs was derived from the data (see Accatino et al.
 209 (2019) for more details), and the driving variables were defined as the land cover fractions and
 210 pesticide expenses for cropland and fodder land. The variables not chosen as driving variables
 211 were considered as constants during the optimisation procedure, as in the initial configuration.

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

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

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

229 For each scenario, some notable outputs provided insights into the effect of spatial level on our
 230 optimisation exercise. First, we observed the total increase in carbon storage at the country
 231 level. Second, the boxplots and maps showed the variability in ES changes across the SARs
 232 for all ESs considered. Third, we observed co-variations of the ESs, which were quantified
 233 with the Spearman coefficient ρ (ranging from -1 , perfect negative correlation, to $+1$, perfect
 234 positive correlation) and indicate the trade-offs and synergies among the ESs. We defined
 235 strong relationships as those with $\rho < -0.5$ (negative) and > 0.5 (positive). Although some ES
 236 trade-offs or synergies have been quantified using correlations among the data or cluster
 237 analyses (see Raudsepp-Hearne et al. 2010; Jopke et al. 2015; Mouchet et al. 2017), we
 238 examined correlations in the results of an optimisation exercise performed with a model that

239 linked drivers to ES, thereby considering causality (Groot and Rossing 2011; Accatino et al.
240 2019).

241

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

247 **3 RESULTS**

248 **3.1 Changes in ecosystem services**

249 The results show that no-loss constraints imposed at larger spatial levels allow for greater
250 improvement of the optimised target ES at the regional scale (Fig. 2). A weak increase in carbon
251 sequestration was noted in the ‘SARs’ scenario, whereas progressively better performances
252 were achieved in the ‘NUTS3’, ‘NUTS2’ and ‘FRANCE’ scenarios, with the latter obtaining
253 the best performance.

254

255 **Fig. 2** Increase in carbon sequestration observed at the country scale in each optimisation scenario. The
256 percentages refer to the variation of the optimised configuration of carbon sequestration from the value
257 corresponding to the initial configuration. All scenarios optimised carbon sequestration but imposed
258 no-loss constraints to other ecosystem services at different spatial extents, namely in each small
259 agricultural region (SAR) (‘SARs’ scenario), NUTS3 area, (‘NUTS3’ scenario) and NUTS2 area
260 (‘NUTS2’ scenario) and in all of France (‘FRANCE’ scenario).

261

262 The variability of the ES variations observed among the SARs increased with the spatial level
263 at which constraints were imposed for all ESs (Fig. 3). The ‘SARs’ scenario was the only one
264 to show no negative variation for ES, which is congruent with the scenario definition (i.e., no
265 loss of any ES at the SAR level). The ‘NUTS3’ scenario showed weak variability with some
266 negative variations at the SAR level. High variability was observed in the ‘NUTS2’ and
267 ‘FRANCE’ scenarios, meaning that local increases in ESs were achieved alongside some local
268 reductions in other ESs. Among all ESs, timber growth showed the least negative variation,
269 mainly due to the strict constraints imposed on forest reductions in the optimisation model.

270

271 **Fig. 3** Boxplots representing the variability of the ecosystem service variations among the small
272 agricultural regions (SARs) for each scenario. All scenarios optimised carbon sequestration but imposed
273 no-loss constraints on other ecosystem services at different spatial extents, namely in each SAR (‘SARs’

274 scenario), NUTS3 area, ('NUTS3' scenario) and NUTS2 area ('NUTS2' scenario) and for all of France
275 ('FRANCE' scenario).

276

277 We mapped the results for the 'NUTS2' and 'FRANCE' scenarios with the same colour scale
278 for each ES (Fig. 4); SAR-level variations in the 'SARs' and 'NUTS3' scenarios were too
279 weak to be observed with the same colour scale. There are evident differences between the
280 'NUTS2' and the 'FRANCE' scenarios. In the 'FRANCE' scenario, the NUTS2 administrative
281 regions have high levels of specialisation, meaning that the SARs in these areas saw a
282 simultaneous increase in one ES and a decrease in another. This is the case, for example, in the
283 northeast of France (Brittany), where carbon sequestration increased in all the SARs as crop
284 and animal production decreased. This was possibly due to an increase in grassland, which
285 allowed for increased carbon sequestration but removed space for crop and livestock
286 production, though it did so to a lesser extent than cereal cultivation for intensive livestock
287 production. Other groups of SARs presented opposite specialisation, such as in the centre of
288 France and the Pyrenees. ES variations were weaker in the 'NUTS2' scenario than in the
289 'FRANCE' scenario. In all NUTS2 areas, for each ES, there were simultaneous increases in
290 some SARs and decreases in others; however, the variations (positive and negative) had
291 different intensities in different NUTS2 areas depending on the land use-related constraints
292 and the diversity of land cover. Some SARs, showed an increase in the 'NUTS2' scenario and
293 a decrease in the 'FRANCE' scenario for the same ESs, or vice versa. Among all the ESs,
294 timber growth showed the lowest difference between the 'NUTS2' and 'FRANCE' scenarios
295 due to the constraints imposed on the forest land cover class.

296

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

300

301 **3.2 Ecosystem services co-variations**

302 The exploration of correlation among couples of ES variations showed significant results;
303 however, few correlations were strong ($|\rho| \geq 0.5$) (Table 1). Carbon sequestration and crop
304 production exhibited a slight trade-off, which was weaker in the 'SARs' and 'NUTS3'
305 scenarios than in the 'NUTS2' and 'FRANCE' scenarios. Synergy was observed between
306 carbon sequestration and timber growth. Interestingly, ρ did not increase monotonously with
307 increasing no-loss constraint levels for carbon sequestration and crop production. Rather, it

308 increased until the ‘NUTS2’ scenario and then decreased for ‘FRANCE’, suggesting that the
 309 strategies implemented to achieve optimisation were different at these scales.

310

311 **Table 1.** Spearman correlation coefficients between coupled variations of ecosystem services in
 312 different scenarios. The correlation coefficient was computed considering the variation of ecosystem
 313 services observed in all the small agricultural regions (SARs) after optimisation. All Spearman
 314 correlation coefficients were statistically significant ($p < 0.001$), except those marked by ‘-’. Legend:
 315 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

316

317

318 4 DISCUSSION

319 By optimising one ES (carbon sequestration) at the regional scale, we explored the influence
 320 of the spatial level of no-loss constraint imposition on potentially conflicting ESs. Two main

321 outcomes were gleaned from the results: 1) There is a trade-off related to the choice of spatial
322 level for no-loss ES management – specifically, implementation at larger levels may cause a
323 greater increase in the target ES but may also increase land cover specialisation and inequalities
324 in the spatial units. In contrast, smaller spatial levels tend to promote local multifunctionality
325 of ESs but cause poorer optimisation performance of the target ES. 2) Trade-offs among ESs
326 can differ according to the level at which the constraints were applied.

327 **4.1 Trade-offs at different spatial levels of no-loss constraints**

328 Increasing the spatial extent of the level at which no-loss constraints are imposed increases the
329 optimisation performance of the targeted ES, which aligns with previous studies. For example,
330 Hölting et al. (2019) found that if the supply of an ES cannot be maximised at one level, another
331 level may be able to better address the goal. Pohjanmies et al. (2017) demonstrated, in their
332 multi-objective optimisation, that the conflict among carbon storage and timber extraction is
333 less strict when the optimisation problem is posed at larger spatial levels. However, the better
334 performance achieved with the no-loss constraints at larger levels comes at a cost: in this case,
335 regions tend to be more specialised in certain ES subsets. Specifically, our study shows that
336 some SARs tend to specialise in crop production and others in carbon sequestration, which is
337 likely to lead to inequalities as some regions may specialise in intensified land uses (Teillard
338 et al. 2017; Shi et al. 2021) with increased use of pesticides and less nature-related land cover
339 (e.g., grassland and forest). This decrease in nature-related land cover in these regions would
340 also decrease other ESs not considered in our modelling, such as recreation potential
341 (Paracchini et al. 2014), erosion control (García-Nieto et al. 2013) and atmospheric NO₂
342 removal (Zulian et al. 2014). In contrast, imposing constraints at a smaller level tends to
343 preserve diversity of land uses locally, softening the inequalities among spatial units. However,
344 this decreases the overall performance of the target ES at the regional scale.

345 Enhancing ES multifunctionality at different levels requires different strategies. Some studies
346 have pointed out that multifunctionality at one level can be obtained through either
347 multifunctionality at smaller scales or mono-functional (but different) smaller-level spatial
348 units (Accatino et al. 2018). The land-sparing and land-sharing debate grew from a need to
349 conciliate biodiversity and agricultural production (Green et al. 2005) but has been extended
350 to conciliation among multiple ESs (Kremen 2015) and scales (Fischer et al. 2014; Accatino
351 et al. 2019). In our study, the ‘FRANCE’ scenario led to land segregation (see also Teillard et
352 al. 2017) at the national scale corresponding to a land-sparing strategy. Conversely, the

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

355

356 **4.2 Trade-offs and synergies among ecosystem services by spatial level**

357 Changing the level at which no-loss constraints were imposed led to changes in the strength of
358 trade-offs and synergies among ESs, which directly aligns with the findings of Bennett et al.
359 (2009). These changes in the spatial extent of imposing no-loss constraints also led to changes
360 in the strategies implemented to address optimisation. Crop production and carbon
361 sequestration are conflicting ESs as they are mostly promoted by different land use types
362 (cropland and grassland/forest, respectively) (Shi et al. 2021). When constraints were imposed
363 at the SAR level, it was difficult to promote the 2 ESs in the same spatial unit. Moreover, when
364 constraints were imposed at larger spatial extents, SARs tended to specialise in one or the other
365 ES, enhancing the trade-off between them.

366 The observed carbon storage and timber growth patterns (increasing synergy strength until the
367 'NUTS2' scenario, but lower strength in the 'FRANCE' scenario) resulted from the difference
368 in land use types associated with these ESs. When forest was promoted to enhance carbon
369 storage, it synergised with timber growth. In the 'FRANCE' scenario, carbon storage was most
370 promoted by an increase in grassland, which created a synergy with livestock production
371 (Accatino et al. 2019) but a trade-off with timber growth. Therefore, a single spatial unit (here,
372 an SAR) can have different fates according to the spatial level at which no-loss constraints are
373 imposed.

374 **4.3 Limits of the study**

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

385 obtained by adding other ESs, we argue that the relative performance obtained in the different
386 scenarios would not have changed.

387 **4.4 Towards an optimal scale**

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

393 Some studies have discussed criteria for setting a preferred spatial level. Mastrangelo et al.
394 (2014) highlighted the preference for the landscape level for enhancing multifunctionality, as
395 this is the level at which multiple and complex relations among stakeholders and land cover
396 and land use types become evident. Other studies have highlighted the importance of
397 considering the scales at which decisions are made, which may relate to specific beneficiary
398 stakeholders (Chan et al. 2006; Raudsepp-Hearne and Peterson 2016). However, decisions are
399 often made at multiple levels (Gitay et al. 2005), and optimal scales can differ among ESs. In
400 addition, also trade-offs in decision making have to be considered (see Zhang et al., 2015).
401 Hence, the contribution of this study lies in highlighting the trade-offs related to the choice of
402 the spatial level. As in Shi et al. (2021), we argue that addressing smaller spatial levels is
403 optimal as it avoids the local environmental impacts of land-sparing strategies (e.g., the local
404 impact of pesticides; see Geiger et al. 2010). A solution more oriented to land-sharing
405 principles, addressing multifunctionality at smaller levels (Schlinder et al., 2014; Pohjanmies
406 et al., 2017), by addressing no-loss strategies at lower spatial levels would lead to lower
407 performance of the ES optimisation at the country scale, though certain efforts could promote
408 practices at the local level based on conservation agriculture and ecological intensification, for
409 example (Schipanski et al. 2014; Autret et al. 2016; Stella et al. 2019)

410 **5 CONCLUSION**

411 Our study showed that when an ES is optimised with no-loss constraints on other ESs, the
412 spatial level at which the constraints are imposed matters. Though larger spatial extents allow
413 for better performance of the targeted ES, they also lead to increased specialisation of
414 landscapes by adopting land-sparing strategies, which may cause social inequalities. In
415 contrast, smaller scales promote and preserve more multifunctional landscapes but allow only
416 modest increases in the target ES. Future research can focus on land cover types that promote
417 multifunctionality at a lower scale (land-sharing strategies) in order to promote local

418 multifunctionality and the optimisation of target ESs. The research of the optimal scale for no-
419 loss ES management can be formalised as an optimisation problem; however, stakeholder
420 involvement and their requirements should also be considered.

421 **6 CONTRIBUTION STATEMENT**

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

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