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

Yong Shi, Alberto Tonda, Francesco Accatino

HAL Id: hal-04068508
https://hal.inrae.fr/hal-04068508v1

Submitted on 21 Jul 2023

1 # Handling ecosystem service trade-offs in France: the importance of the

2 # level at which no-loss constraints are posed

3 Yong Shi[1], Alberto Tonda[2], Francesco Accatino[3,*]

4 [1] China University of Geosciences, Lumo Road, 430074, Wuhan, China

5 [2] UMR 518-MIA, INRAE, AgroParisTech, Université Paris-Saclay, 75013, Paris, France

6 [3] UMR SADAPT, INRAE, AgroParisTech, Université Paris-Saclay, 94200, Ivry sur Seine, France

7

8 [*] corresponding author: Francesco Accatino, francesco.accatino@inrae.fr, UMR SADAPT, INRAE,
9 AgroParisTech, Université Paris-Saclay, 65, Boulevard de Brandebourg, 94200, Ivry sur Seine,
10 France. Tel: +33149696915

11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

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

2

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.

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*

5

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 (ºC). The ESs considered were carbon sequestration (CS), crop production (

188 CP), 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

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

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

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

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.

6

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:

$$max\left(\sum_{j \in F} E_{CS,j}\right)$$

$$\sum_{j \in \Omega_h} E_{k,j} \geq \sum_{j \in \Omega_h} E_{k,j}^0 \qquad \forall h, \forall k \in \{CP, LP, TG\} \qquad (3)$$

$$\sum_{j \in \Omega_h} \Theta_j \leq \sum_{j \in \Omega_h} \Theta_j^0 \qquad \forall h, \forall k \in \{CP, LP, TG\}$$

219

220 where F represents all the SARs in France; Θ_j is the total pesticide expenses (in cropland and
221 fodder land) in SAR j; and Ω_h represents sets of SARs and is distinct for different scenarios.
222 In the first scenario ('SARs'), Ω_h represents each SAR; in the second scenario ('NUTS3'), Ω_h
223 represents each metropolitan French department; in the third scenario ('NUTS2'), Ω_h
224 represents each metropolitan French administrative region; and in the fourth scenario
225 ('FRANCE'), a single $\Omega_h = F$, corresponding to all the SARs in France. Figure 1 presents the
226 boundaries within which the no-loss constraints were applied. Other SAR-specific constraints,
227 described in Accatino et al. (2019), were applied to limit the maximum extent to which the
228 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.

3 RESULTS

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'

8

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

9

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

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.

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 NO_2
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

13

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.

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.

7 ACKNOWLEDGMENTS

8 REFERENCE LIST

428 Accatino F, Creed IF, Weber M (2018) Landscape consequences of aggregation rules for
429 functional equivalence in compensatory mitigation programs. Conserv Biol
430 32:694–705

431 Accatino F, Tonda A, Dross C, et al (2019) Trade-offs and synergies between livestock
432 production and other ecosystem services. Agric Syst 168:58–72.
433 https://doi.org/10.1016/j.agsy.2018.08.002

434 Autret B, Mary B, Chenu C, Balabane M, Girargìn C et al (2016) Alternative arable cropping
435 systems: a key to increase soil organic carbon storage? Results from a 16 year field
436 experiment. Agric Ecosyst Environ 232: 150-164.
437 https://doi.org/10.1016/j.agee.2016.07.008

438 Anderson CR, Moore SK, Tomlinson MC, et al (2015) Living with harmful algal blooms in a
439 changing world: strategies for modeling and mitigating their effects in coastal marine
440 ecosystems. In: Coastal and Marine Hazards, Risks, and Disasters. Elsevier, pp
441 495–561

442 Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple
443 ecosystem services. Ecol Lett 12:1394–1404. https://doi.org/10.1111/j.1461-
444 0248.2009.01387.x

445 Bouwma I, Schleyer C, Primmer E, et al (2018) Adoption of the ecosystem services concept in
446 EU policies. Ecosyst Serv 29:213–222. https://doi.org/10.1016/j.ecoser.2017.02.014

447 Butsic V, Kuemmerle T (2015) Using optimization methods to align food production and
448 biodiversity conservation beyond land sharing and land sparing. Ecol Appl 25:589–595.
449 https://doi.org/10.1890/14-1927.1

450 Chan KMA, Shaw MR, Cameron DR, et al (2006) Conservation planning for ecosystem
451 services. PLoS Biol 4:e379

452 Ericksen PJ, Ingram JS, Liverman DM (2009) Food security and global environmental change:
453   emerging challenges. https://doi.org/10.1016/j.envsci.2009.04.007

454 European commission (EC) (2020), Communication from the commission to the European
455   parliament, the council, the European economic and social committee and the
456   committee of the regions: EU Biodiversity Strategy for 2030, Bringing nature back into
457   our lives.

458 Fischer J, Abson DJ, Butsic V, Chapperll M, Ekroos J et al (2014) Land sparing versus land
459   sharing: moving forward. Conserv Lett 7: 149-157. https://doi.org/10.1111/conl.12084

460 Foley JA, Ramankutty N, Brauman KA, et al (2011) Solutions for a cultivated planet. Nature
461   478:337–342. https://doi.org/10.1038/nature10452

462 García-Nieto AP, García-Llorente M, Iniesta-Arandia I, Martín-López B (2013) Mapping
463   forest ecosystem services: from providing units to beneficiaries. Ecosyst Serv
464   4:126–138

465 Geiger F, Bengtsson J, Berendse F, Weisser WW, Emmerson M et al (2010) Persistent negative
466   effects of pesticide on biodiversity and biological control potential on European
467   farmland. Basic Appl Ecol 11:97-105. https://doi.org/10.1016/j.baae.2009.12.001

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

469 Godfray HCJ, Beddington JR, Crute IR, et al (2010) Food security: the challenge of feeding 9
470   billion people. Science 327:812–818

471 Grêt-Regamey A, Weibel B, Bagstad KJ, et al (2014) On the effects of scale for ecosystem
472   services mapping. PloS One 9:e112601

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

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

477 Hölting L, Jacobs S, Felipe-Lucia MR, et al (2019) Measuring ecosystem multifunctionality
478   across scales. Environ Res Lett 14:124083

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

482 Kon Kam King J, Granjou C, Fournil J, Cecillon L (2018) Soil sciences and the French 4 per
483   1000 Initiative—The promises of underground carbon. Energy Res Soc Sci 45:144–152

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

486 Lindborg R, Gordon LJ, Malinga R, et al (2017) How spatial scale shapes the generation and
487   management of multiple ecosystem services. Ecosphere 8:e01741

15

488 Mastrangelo ME, Weyland F, Villarino SH, et al (2014) Concepts and methods for landscape
489   multifunctionality and a unifying framework based on ecosystem services. Landsc Ecol
490   29:345–358

491 MEA (2005) Ecosystems and Human Well-Being: wetlands and water synthesis

492 Metzger Mj, Rounsevell M, Acosta-Michlik L, et al (2006) The vulnerability of ecosystem
493   services to land use change. Agric Ecosyst Environ 114:69–85

494 Mouchet M, Paracchini M, Schulp C, et al (2017) Bundles of ecosystem (dis) services and
495   multifunctionality across European landscapes. Ecol Indic 73:23–28

496 Musacch

497 Nelson E, Mendoza G, Regetz J, et al (2009) Modeling multiple ecosystem services,
498   biodiversity conservation, commodity production, and tradeoffs at landscape scales.
499   Front Ecol Environ 7:4–11

500 Paracchini ML, Zulian G, Kopperoinen L, et al (2014) Mapping cultural ecosystem services:
501   A framework to assess the potential for outdoor recreation across the EU. Ecol Indic
502   45:371–385

503 Pohjanmies T, Eyvindson K, Triviño M, Mönkkönen M (2017) More is more? Forest
504   management allocation at different spatial scales to mitigate conflicts between
505   ecosystem services. Landscape Ecol 32:2337-2349

506 Pinsard C, Martin S, Léger F, Accatino F (2021) Robustness to import declines of three types
507   of European farming systems assessed with a dynamic nitrogen flow model. Agric Syst
508   193:103215

509 Qiu S, Yue W, Zhang H, Qi J (2017) Island ecosystem services value, land-use change, and
510   the National New Area Policy in Zhoushan Archipelago, China. Isl Stud J 12:

511 Raudsepp-Hearne C, Peterson GD (2016) Scale and ecosystem services: how do observation,
512   management, and analysis shift with scale—lessons from Québec. Ecol Soc 21:

513 Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for
514   analyzing tradeoffs in diverse landscapes. Proc Natl Acad Sci 107:5242–5247

515 Rodríguez JP, Beard Jr TD, Bennett EM, et al (2006) Trade-offs across space, time, and
516   ecosystem services. Ecol Soc 11:

517 Ruijs A, Wossink A, Kortelainen M, et al (2013) Trade-off analysis of ecosystem services in
518   Eastern Europe. Ecosyst Serv 4:82–94. https://doi.org/10.1016/j.ecoser.2013.04.002

519 Schlinder S, Sebasvari Z, Damm C., Euller K, Mauerhofer V, et al (2014). Multifunctionality
520   of foodplain landscapes: relating management options to ecosystem services.
521   Landscape Ecol 29: 229-244.

522 Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K et al (2014) A framework
523   for evaluating ecosystem services provided by cover crops in agroecosystems. Agr Sys
524   125: 12-22. https://doi.org/10.1016/j.agsy.2013.11.004

525 Scholes RJ, Reyers B, Biggs R, et al (2013) Multi-scale and cross-scale assessments of
526   social–ecological systems and their ecosystem services. Curr Opin Environ Sustain
527   5:16–25

528 Seppelt R, Lautenbach S, Volk M (2013) Identifying trade-offs between ecosystem services,
529   land use, and biodiversity: a plea for combining scenario analysis and optimization on
530   different spatial scales. Curr Opin Environ Sustain 5:458–463

531 Shi Y, Pinsard C, Accatino F (2021) Land sharing strategies for addressing the trade-off
532   between carbon storage and crop production in France. Reg Environ Change 21:1–14

533 Stella T, Mouratiandou I, Gaiser T, Berg-Mohnicke M, Wallor E, et al. (2019) Estimating the
534   contribution of crop residues to soil organic carbon conservation. Environ Res Lett 14.
535   https://doi.org/10.1088/1748-9326/ab395c

536 Stürck J, Verburg PH (2017) Multifunctionality at what scale? A landscape multifunctionality
537   assessment for the European Union under conditions of land use change. Landsc Ecol
538   32:481–500

539 Tallis H, Polasky S (2011) Assessing multiple ecosystem services: an integrated tool for the
540   real world. Nat Cap Theory Pract Mapp Ecosyst Serv 34–50

541 Teillard F, Doyen L, Dross C, et al (2017) Optimal allocations of agricultural intensity reveal
542   win-no loss solutions for food production and biodiversity. Reg Environ Change
543   17:1397–1408. https://doi.org/10.1007/s10113-016-0947-x

544 Zhang L, Fu B, Lü Y, Zeng Y (2015). Balancing multiple ecosystem services in conservation
545   priority setting. Landscape Ecol 30:535-546.

546 Zulian G, Polce C, Maes J (2014) ESTIMAP: a GIS-based model to map ecosystem services
547   in the European Union. Ann Bot 4:1–7

548