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# 1 **Trade-offs and synergies between livestock production**

## 2 **and other ecosystem services**

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18

## 19 **Abstract**

20 One of the biggest challenges today is to satisfy an increasing food demand while  
21 preserving ecosystem services. Farming systems have a huge impact on land cover and  
22 land use, it is therefore vital to understand how land cover and land use allocation can  
23 promote synergies between food production and other ecosystem services. Livestock  
24 production has multiple interactions with other ecosystem services and can promote  
25 synergies especially in grasslands. We investigated the interactions between livestock  
26 production and other ecosystem services and explored strategies to soften trade-offs and  
27 enhance synergies. We considered four ecosystem services (livestock production, crop  
28 production, carbon sequestration, and timber growth) in France. We considered 709 land  
29 units covering a wide range of farming systems where both food production and other  
30 ecosystem services are provided. For each land unit, we built ecological production  
31 functions that are models measuring the statistical influence of driving variables (i.e. land  
32 cover, land use, pesticide expense, and climate) on the provision of ecosystem services.  
33 Using an optimization procedure, we studied the extent to which livestock production  
34 could be increased without reducing other ecosystem services and without increasing  
35 total pesticide expense. We found that a 20% increase in livestock production could be  
36 achieved by all farming systems in France under those general constraints. The 709 land  
37 units could be grouped based on similar combinations of increases or decreases in  
38 specific ecosystem services during the optimization. 45% of land units were specialised  
39 on food production, whereas 32% were specialised on other ecosystem services. The  
40 remaining 23% were specialized on the mixed provision of food production and other  
41 ecosystem services. Livestock production was either in trade-off or in synergy with the

42 other ecosystem services. The trade-offs could be softened through intensified use of  
43 cultivated land and spatial segregation of livestock production. The synergies could be  
44 enhanced only through major grassland expansion.

## 45 **Keywords**

46 livestock production, ecosystem service, trade-off, synergy, grassland

47

## 48 **1. Introduction**

49 With the increasing size of the human population, the global food requirement is  
50 expected to rise abruptly by 2050 (Tilman et al., 2011; Kastner et al., 2012). In particular,  
51 rising incomes are expected to increase the global demand for animal products (Godfray  
52 et al., 2010; Thornton, 2010; Aleksandratos and Bruinsma, 2012; Mottet et al. 2017). It  
53 will be difficult to satisfy the increasing demand for animal products; however, the real  
54 challenge will be to satisfy that demand while also protecting the environment  
55 (Sutherland et al., 2006; Ericksen et al., 2009). To help meet that challenge, the  
56 Millenium Ecosystem Assessment (MEA, 2005) recognised ecosystem services, the  
57 benefits that nature provides to human society, as fundamental components of sustainable  
58 development.

59 Several authors have pointed out that focusing on the production of a single ecosystem  
60 service can negatively affect the provision of other ecosystem services, because trade-offs  
61 exist between different ecosystem services (Bennett et al., 2009; Seppelt et al., 2013).  
62 Therefore, it is important to understand how food production is interrelated with other  
63 ecosystem services (Zhang et al., 2007; Power, 2010; Foley et al., 2011) in order to

64 identify strategies to soften trade-offs and promote synergies (Dumont et al., 2013).  
65 Livestock production, in particular, has been recognised as having the potential to  
66 influence multiple ecosystem services (Herrero and Thornton, 2013). A recent study by  
67 Rodríguez-Ortega et al. (2014) reviewed the trade-offs and synergies between pasture-  
68 based livestock production and other types of ecosystem services at different spatial  
69 scales. They highlighted the need for new, more quantitative analyses of the linkages  
70 between pasture-based livestock production and other ecosystem services.

71 Farming systems are among the principal drivers of land cover and land use allocation  
72 and their total impact can profoundly transform land surface on a large scale ([Lovell et  
73 al., 2010], and see the scenarios for Europe by Holman et al., [2017]). These  
74 transformations are among the most important drivers of the anthropogenic effects on  
75 ecosystem services (Foley et al., 2005; Metzger et al., 2006; Tsonkova et al., 2015).

76 Livestock production impacts both directly and indirectly on land use. The direct impacts  
77 correspond to the vast areas of pasture and grassland used for livestock grazing, while the  
78 indirect impacts correspond to feed production (Ramankutty et al., 2008). Roughly, at the  
79 global level, the 25% of agricultural land is dedicated to grazed land while about the 15%  
80 is used for forage crops (Monfreda et al., 2008; Ramankutty et al., 2008). Agricultural  
81 production causes trade-offs with other ecosystem services. Agricultural land expansion  
82 is the most important driver of losses of ecosystem services (Foley et al., 2005). In  
83 addition, the intensification of land use for food and feed production negatively impacts  
84 on biodiversity and other ecosystem services (Hallmann et al., 2014; Teillard et al.,  
85 2016). Grasslands promote synergies between ecosystem services, because they can  
86 provide agricultural production as well as other ecosystem services (e.g. carbon

87 sequestration [Soussana and Lemaire, 2004] and biodiversity [Lemaire et al., 2005;  
88 Sabatier et al., 2015; Teillard et al., 2015; Dross et al., 2018]). In addition, grassland  
89 would increase livestock production without using pesticides, which are, instead, used in  
90 fodder cultivation.

91 To better understand the relationships between livestock production and other ecosystem  
92 services, as well as identifying measures in farming systems to overcome the trade-offs, it  
93 is important to study the drivers of trade-offs and synergies between ecosystem services  
94 (Bennett et al., 2009; Rodríguez-Ortega et al., 2014). Such study requires an  
95 understanding of the linkages between the drivers and the ecosystem services.

96 Correlation-based analyses (Chan et al., 2006; Jopke et al., 2014) and cluster analyses  
97 (Raudsepp-Hearne et al., 2010; Morelli et al., 2017) provide information about the co-  
98 occurrence of ecosystem services; however, they ignore the linkages to drivers, which  
99 must be understood in order to find management strategies that soften trade-offs and  
100 enhance synergies.

101 Optimization techniques are useful for studying the relationships among two or more  
102 ecosystem services (Groot and Rossing, 2011). They have been used to explore the trade-  
103 offs between contrasting objectives in Pareto frontiers (Groot et al., 2010; 2015), food  
104 production and biodiversity (Teillard et al., 2016; Dross et al., 2017; 2018), and economic  
105 return and biodiversity (Polasky et al., 2008). They have also been used to maximise one  
106 objective while imposing constraints of no-loss on other objectives (Butsic and  
107 Kuemmerle 2015) and to systematically explore management variables and identify  
108 solutions (Seppelt et al., 2013). While some optimization scenarios were formulated for  
109 the trade-off between agriculture and biodiversity, a lower effort was put on the

110 relationship between livestock production and other ecosystem services, implying that  
111 these relationships have been hypothesized theoretically but not explored in a more  
112 quantitative way with an optimization model.

113 We investigated the performance of a large set of alternative land cover and land use  
114 allocations across the whole of France, identifying trade-offs and synergies between  
115 livestock production and other ecosystem services. We explored strategies to soften the  
116 trade-offs and enhance the synergies. We hypothesized (following more qualitative  
117 studies [e.g., Rodriguez-Ortega et al., 2014]) that grasslands promoted synergies between  
118 livestock production and other ecosystem services with the additional advantage of  
119 increasing livestock production without increasing the use of pesticides. Our modelling  
120 approach served to provide quantitative information about the extent to which this could  
121 be achieved. Also, we quantified the extent to which conflicts between the ecosystem  
122 services could be softened, considering the different constraints posed on land cover and  
123 land use change, and discuss the consequences of the strategies proposed by the model.

124 We divided France in 709 land units, each of them corresponding to the spatial extension  
125 of a farming system. For each land unit, we built and calibrated with data ecological  
126 production functions (EPFs; Tallis and Polasky, 2011) that predicted the provision of  
127 ecosystem services (i.e., livestock production, crop production, carbon sequestration, and  
128 timber growth) based on land cover, land use, and climatic variables. We used the EPFs  
129 to formulate a constrained Optimization problem in which we sought to optimise total  
130 French livestock production while imposing constraints of no loss on the total provision  
131 of the other three ecosystem services.

132

## 133 2. Methods

134 We defined the set  $R$  of regions, being each region representative of the area of a farming  
135 system, corresponding to a set of farms in a particular geographic location (Giller, 2013).  
136 Within each region  $r$ , the management area  $A_r$  [ha] is defined as the portion of land  
137 containing different land covers that provide ecosystem services. We defined  $S$  as the set  
138 of ecosystem services. Being  $s \in S$ , we defined  $w_{s,r}$  as the amount of ecosystem service  $s$   
139 provided in the management area of the region  $r$ . The set  $S$  is formed by livestock  
140 production ( $LP$ ) [Mcal yr<sup>-1</sup>], crop production ( $CP$ ) [Mcal yr<sup>-1</sup>], carbon sequestration ( $CS$ )  
141 [gC yr<sup>-1</sup>], and timber growth ( $TG$ ) [m<sup>3</sup> yr<sup>-1</sup>]. Livestock production represents the sum of  
142 the energy contained in meat and milk products from ruminants (dairy and beef cattle,  
143 goats, and sheep). Altogether, those species contribute to 68% of the total French national  
144 protein production. We excluded pigs and poultry, because those species are more  
145 dependent on feed imports and are thus less related to the land than the ruminants.  
146 Carbon sequestration represents the flux of carbon subtracted from the atmosphere, which  
147 we assume to be a proxy for the capacity of the land cover to mitigate climate change.  
148 Timber growth represents the annual amount of timber produced by broadleaf and  
149 coniferous forests (Gallaun et al., 2010). Analogously to the set of ecosystem services,  
150 we also define the set  $M$  of environmental impacts, where, being  $m \in M$ ,  $w_{m,r}$  represents  
151 the amount of environmental impact  $m$  produced in the management area of region  $r$ . In  
152 this set, we only consider the pesticide expense  $PE$ , which represents the total amount of  
153 pesticide expense used for crop and fodder cultivation.

154 We defined a set  $D$  of decision variables. Being  $d$  the generic variable, the quantity  $\theta_{d,r}$   
155 represents the value of the decision variable  $d$  in the region  $r$ . A combination of values of



156 all the decision variables in a region is denoted by  $\times_{d \in D} \{\theta_{d,r}\}$  and provides a value  $w_{s,r}$   
157 of an ecosystem service  $s$  through a function  $f_{s,r}(\times_{d \in D} \{\theta_{d,r}\})$  and a value  $w_{s,r}$  of  
158 environmental impact  $m$  through a function  $f_{m,r}(\times_{d \in D} \{\theta_{d,r}\})$  The optimization starts  
159 from an actual combination of decision variables in all the regions, denoted by  $\times$   
160  $\{\bar{\theta}_{d,r}\}$ , corresponding to actual values of ecosystem services  $\bar{w}_{s,r}$  in the different  
161 regions, explores different combinations of the decision variables in all the regions in  
162 order to find the optimal combination of decision variables  $\times_{d \in D, r \in R} \{\theta_{d,r}^*\}$  corresponding  
163 to target ecosystem services  $w_{s,r}^*$  and target environmental impact  $w_{m,r}^*$  in the different  
164 regions.

165 In the optimization problem, we seeked to maximize the total livestock production in all  
166 the regions under some constraints

$$\max \left( \sum_{r \in R} f_{LP,r}(\times_{d \in D} \{\theta_{d,r}\}) \right) \quad \text{Eq. (1)}$$

167 With the constraints

$$\theta_{d,r} \in \Theta_{d,r}, \quad \forall d \in D, \quad \forall r \in R \quad \text{Eq. (2)}$$

$$\sum_{r \in R} f_{s,r}(\times_{d \in D} \{\theta_{d,r}\}) \geq \sum_{r \in R} \bar{w}_{s,r}, \quad \forall s \in \{CP, CS, TG\} \quad \text{Eq. (3)}$$

$$\sum_{r \in R} f_{PE,r}(\times_{d \in D} \{\theta_{d,r}\}) \leq \sum_{r \in R} \bar{w}_{PE,r} \quad \text{Eq. (4)}$$

168

169 Eq. (1) represents the target optimization of livestock production at the whole national  
170 scale (it is the sum of the livestock production in all regions). Eq. (2) represents the

171 constraints posed on decision variables themselves. By definition, decision variables are  
172 included in some ranges, however there are additional region-specific constraints denoted  
173 by  $\Theta_{d,r}$ . Eq. (3) describes the constraint of no-loss on the ecosystem services other than  
174 livestock production: the total provision of those ecosystem services at the national level  
175 should not be lower than the one corresponding to the initial configuration of the decision  
176 variables. The last constraint (Eq. (4)) indicates that the total pesticide expense in the  
177 optimized configuration cannot be greater than the total pesticide expense corresponding  
178 to the initial configuration. Table 1 summarizes all notations used in our modelling  
179 framework.

180

## 181 **2.1 Application to France**

### 182 *2.1.1 Formulation of the ecological production functions for ecosystem services*

183 We applied the optimization model to France. As regions, we considered the Small  
184 Agricultural Region (SAR), that are elementary land units in France homogeneous in  
185 climate and soil (Klatzmann, 1955), containing land covers for both provisioning and  
186 regulating ecosystem services and approximating the area of a farming system. SARs  
187 have been successfully used in several studies of food production and biodiversity  
188 modelling (e.g. Mouysset et al., [2011], Princé et al., [2013], and Teillard et al. [2016]).  
189 In France, there are 714 SARs with an average area of 669.6 km<sup>2</sup>. We considered in our  
190 study 709 SARs, specifically excluding Paris and the four SARs around Paris, which are  
191 highly urbanized.

192 For calculating the provision of ecosystem services we defined EPFs starting from land  
 193 cover, land use, and climate variables. We assumed that each land cover fraction provides  
 194 a certain amount of ecosystem services according to a Cobb-Douglas function, where  
 195 different production factors correspond to land use and climate variables. Considering  
 196 that a process-based model was too complicated to formulate and calibrate, we opted for  
 197 a statistical model that could be calibrated with data. A Cobb-Douglas function, being a  
 198 weighted product of production factors, provides a limited amount of substitutability  
 199 between production factors, differently from a linear combination that would assume  
 200 complete substitutability. The Cobb-Douglas function is furthermore widely used as a  
 201 simple but efficient model in economy, with application on pure ecology (Barbier, 2007)  
 202 or economic-ecologic applications (Boumans et al., 2002; Onofri et al., 2017).

203 We defined  $L$  as the set of land cover fractions,  $U$  as the set of the land-use-related  
 204 production factors, and  $C$  as the set of climate-related production factors. Each element  $l$   
 205 of the land cover fraction is associated to a set  $Z_l$  of fraction into which it is sub-divided.  
 206 The values associated to elements of  $Z_l$  sum up to 1 for each  $l$ . The generic formulation  
 207 of the EPF for the ecosystem service  $s$  in the SAR  $r$  is described by:

$$w_{s,r} = A_r \sum_{l \in L} \sum_{z \in Z_l} \alpha_{s,l,z} \cdot \theta_{l,r} \cdot \theta_{l,z,r} \cdot \left( \prod_{u \in U} \theta_{u,r}^{\gamma_{s,u,l,z}} \prod_{c \in C} \theta_{c,r}^{\gamma_{s,c,l,z}} \right) \quad \text{Eq. (5)}$$

208 See Table 1 for the detailed descriptions of the elements in the equations. Parameter  $\alpha_{s,l,z}$   
 209 is a coefficient specific to the ecosystem service  $s$ , and to the sub-fraction  $z$  of the land  
 210 cover  $l$ . Parameter  $\gamma_{s,u,l,z}$  is the exponent of the land-use-related production factor  $u$ ,  
 211 specific to the ecosystem service  $s$  and to the fraction  $z$  of the land cover  $l$ . Parameter

212  $\gamma_{s,c,l,z}$  is the exponent of the climate-related production factor  $u$ , specific to the ecosystem  
213 service  $s$  and to the fraction  $z$  of the land cover  $l$ . The coefficients of the land uses as well  
214 as the exponents of the production factors represent the parameters of the Cobb-Douglas  
215 function, are independent of the SAR and are parameterized with data following the  
216 procedure described in Section 2.2.7.

217 The set  $L$  of land cover variables is formed by fodderland  $FOD$  (arable land supporting  
218 livestock feeding), cropland  $C$  (arable land supporting crops for human consumption),  
219 non-permanent grassland  $NPG$ , permanent grassland, and forest  $F$ . The values associated  
220 to these variables in the SAR  $r$ ,  $\theta_{l,r}$ , represent fractions of the management area  $A_r$ , they  
221 range between 0 and 1, and they sum up to one. The land cover fractions  $FOD$ ,  $C$ ,  $NPG$   
222 are not sub-divided into fractions, therefore the set of their sub-fractions is formed by one  
223 element with value equal to 1. Land cover fraction  $PG$  is composed by two subcategories  
224  $PG_{(231)}$  and  $PG_{(321)}$ , namely (following the Corine Land Cover [CLC] nomenclature  
225 [EEA, 2013]) *Pasture* (CLC category 231, put in superscript) and *Natural Grassland*  
226 (CLC 321), respectively. Land cover fraction  $F$  is composed by five sub-categories,  
227 namely *Broad Leaved Forest* (CLC 311), *Coniferous Forest* (CLC 312), *Mixed Forest*  
228 (CLC 313), *Sclerophyllous Vegetation* (CLC 323), and *Transitional Woodland-Shrub*  
229 (CLC 324), respectively.

230 The set of land-use-related production factors,  $U$ , is formed by the annual pesticide  
231 expense [ $\text{€ ha}^{-1} \text{ yr}^{-1}$ ] per unit area of fodderland and cropland,  $p_{FOD}$  and  $p_C$ , as well as the  
232 production factor  $k$  [Mcal], which represents the average crop energetic content in the  
233 cropland fraction. Such a production factor is a proxy of the crop associations in the  
234 different parts of the country. We denote by  $\theta_{u,r}$ ,  $u \in U$ , their values in the SAR  $r$ . The set

235 of climate-related production factors,  $C$ , is formed by average annual precipitation  $P$  [mm  
236  $\text{yr}^{-1}$ ] and average annual temperature  $T$  [ $^{\circ}\text{C}$ ]. We denoted by  $\theta_{c,r}$ ,  $c \in C$ , their values in the  
237 SAR  $r$ .

### 238 *2.2.2 Formulation of the function for the environmental impact*

239 The total expense in pesticide [ $\text{€ yr}^{-1}$ ] in the SAR  $r$  constitutes an output of the model and  
240 is obtained with this formula:

$$w_{PE,r} = (\theta_{FOD,r} \theta_{p_{FOD,r}} + \theta_{C,r} \theta_{p_{C,r}}) A_r \quad \text{Eq. (6)}$$

### 241 *2.2.3 Definition of the decision variables*

242 As decision variables we choose all the land use fractions of set  $L$  ( $FOD$ ,  $C$ ,  $NPG$ ,  $PG$ ,  $F$ )  
243 and the annual pesticide expenses per unit area of cropland and fodderland ( $p_{FOD}$  and  
244  $p_C$ ). The elements not chosen as decision variables ( $k$ ,  $T$ ,  $C$  and the sub-fractions of  $PG$   
245 and  $F$ ) were kept constant along the optimization procedure and are therefore considered  
246 as parameters of the model. The choice of keeping  $k$  constant, corresponds to the  
247 assumptions that crop associations in the different SARs are the result of historic  
248 optimization given the local pedo-climatic conditions (Heck et al., 2018). The choice of  
249 keeping climate-related production factors constant translates that climate variables are  
250 characteristics of the SARs, as well as the management area. By considering as constants  
251 the sub-fractions of  $PG$  and  $F$ , we reduced the number of decision variables involved in  
252 the optimization process while still accounting for the contribution of a larger number of  
253 land cover types in the provision of ecosystem services.

### 254 *2.2.4 Constraints on the decision variables*

255 We posed SAR-specific constraints on the decision variables, defining the set  $\theta_{d,r}$  of Eq.  
256 (2). These constraints were posed for three reasons: (1) The model being calibrated for  
257 France, the decision variables cannot go outside the data used for model calibration; (2)  
258 the decision variables cannot be too different from the historic land cover or land uses in  
259 the different parts of France, in order to avoid unrealistic solutions; (3) there are  
260 biophysical and political constraints in the different parts of France. Details about the  
261 constraints on decision variables are described in Appendix 1. Constraints did not made  
262 changes possible in cropland and fodderland mostly in pastoral and mountain areas  
263 (14.5% of SARs), they did not made change possible in forest in 15% of the SARs,  
264 however they still enabled considerable expansion and reduction of land covers in  
265 different parts of the country and at the whole country level. At the French level, the total  
266 forest area could vary between -2% and +5% of its actual value, the total grassland area  
267 could change between -16% and +46% of its actual value and the other land uses could  
268 change at least between -41% and +29% of their actual value. The total pesticide expense  
269 at the French level in cropland and fodderland could change between at least -53% and  
270 +48% of its actual value.

### 271 *2.2.5 Optimization procedure*

272 The optimization problem was non-linear, with a considerable number of constraints on  
273 each decision variable. Therefore, we used an optimization technique based on an  
274 evolutionary algorithm (De Jong, 2006), which is the most suitable to escape local  
275 optima. The evolutionary algorithms do not always find the local optimum, however they  
276 can explore efficiently the space of the solutions and provide a first quantitative  
277 assessment of how livestock production could be increased in the respect of the

278 constraints. Finding the exact optimum was out of our purpose. With a sub-optimal  
279 solution we were able to analyse how decision variables were changed and to discuss  
280 land cover and land use techniques for addressing trade-offs and synergies between  
281 ecosystem services. Evolutionary algorithms have been used previously in land use  
282 models (Teillard et al., [2016]; Groot et al., [2010]; and see Memmah et al. [2015] and  
283 the methodological paper of Groot and Rossing [2011]). The procedure is based on a  
284 state-of-the-art optimiser, the Covariance Matrix Adaptation Evolution Strategy (CMA-  
285 ES; Hansen and Ostermeier, 2001), implemented in Python. We chose that algorithm for  
286 its efficiency in tackling non-convex problems and the ease with which user-defined  
287 constraints can be introduced into the objective function.

#### 288 2.2.6 Data

289 We used existing data to calibrate the EPFs (Eq. [5]) and to initialise the optimization  
290 procedure at the national level. To calibrate the EPFs, we used existing data to obtain  
291 values for the land use fractions and sub-fractions, the land-use-related and the climate-  
292 related production factors (model inputs) and for the ecosystem services (model outputs).  
293 We focused on data from 2006, because that was the year for which the most data were  
294 available for all of the variables. We took a few datasets from different years, because  
295 data for some variables were unavailable for 2006.

296 We computed the areas dedicated to cropland, fodderland, non-permanent grassland, and  
297 permanent grassland in each SAR based on annual agricultural statistics (*statistiques*  
298 *agricoles annuelles*; Dross et al. 2017). We estimated the fraction of forest in each SAR,  
299 as well as the sub-fractions of forest and permanent grassland based on the CLC layers  
300 (EEA, 2013). We extracted rainfall and temperature data from the dataset of Haylock et

301 al., (2008). We obtained the energetic content of the crops in the SARs from Dross et al.  
302 (2017). For the pesticide expense in the cropland and fodderland, we used the data set  
303 estimated by Butault et al. (2010) for 2006.

304 We obtained data of 2006 for crop and livestock production at the SAR level from Dross  
305 et al. (2017). For carbon sequestration and timber growth, we used layers fully described  
306 in Maes et al. (2011). The carbon sequestration layer consisted of a  $1 \text{ km}^2 \times 1 \text{ km}^2$  grid  
307 that Veroustraete et al. (2002) produced to model carbon sequestration starting from the  
308 Normalized Difference Vegetation Index (NDVI). The timber growth layer came from  
309 the work of Gallaun et al. (2010), which combined national forest inventory data and  
310 remotely sensed vegetation data (MODIS).

### 311 *2.2.7 Model calibration*

312 We calibrated the parameters  $\alpha_{s,l,z}$ ,  $\gamma_{s,u,l,z}$  and  $\gamma_{s,c,l,z}$  for the EPF dedicated to each  
313 ecosystem service. The calibration procedure was computed with CMA-ES (Hansen and  
314 Ostermeier, 2001), implemented in Python, minimizing the sum of the differences in the  
315 different SARs between measured and modelled ES. The optimization procedure  
316 included expert-assessed constraints on the relative values of the parameters in order to  
317 ensure that the model was realistic (e.g., the carbon sequestered by a unit of forest area  
318 unit should be greater than that sequestered by a unit of cropland). Because the  
319 calibration was done with the values of the land use variables corresponding to the initial  
320 configuration, applying Eq.(5) using the values  $\bar{\theta}_{d,r}$ , the values  $\bar{w}_{s,r}$  are obtained, for each  
321 decision variable  $d$ , SAR  $r$ , and ecosystem services  $s$ . No relationships were imposed a-  
322 priori between the parameters. For the ecosystem services, only the relationships depicted  
323 in Figure 1 were considered (where the arrow is absent between the variable and the



324 ecosystem service, the coefficient was not estimated but was instead set to zero). The  
325 parameter and  $R^2$  values are shown in Table 2. In all the land covers, for livestock  
326 production, carbon sequestration and timber growth, the sum of the exponents of the  
327 Cobb-Douglas function was lower than one, indicating a decreasing return to scale, i.e.,  
328 the ecosystem services increased less than linearly with the production factors  
329 considered. The only exponents showing an increasing return to scale was the crop  
330 association parameter. Crop production increased more than linearly with crop  
331 composition, indicating that highly productive crops can be in synergy and increase the  
332 total yield.

333

### 334 **2.3 Analysis of the optimization results**

335 After the optimization procedure, we divided the SARs into groups that were  
336 homogeneous for the signs of the changes (positive or negative) registered in the values  
337 of the different ecosystem services during the optimization process (Section 2.3.1).  
338 Within each group, we analysed the changes in the drivers causing the variation in  
339 ecosystem services (Section 2.3.2).

#### 340 *2.3.1 Grouping of the SARs based on similar changes in ecosystem services*

341 We normalised the increases or decreases in ecosystem services in the different SARs.  
342 For each SAR  $r$ , we calculated the change in the value of each ecosystem service per unit  
343 of management area:

$$\Delta w_{s,r} = \frac{(w_{s,r}^* - \bar{w}_{s,r})}{A_r} \quad \text{Eq. (7)}$$

344

345 We then normalized the ecosystem service provision as follows:

346

$$\tilde{\Delta w}_{s,r} = \frac{\Delta w_{s,r}}{\max_{r \in R} (abs(\Delta w_{s,r}))} \quad \text{Eq. (8)}$$

347

348 The normalisation produced values ranging from -1 to 1, maintaining the positivity or  
349 negativity of the changes in the levels of ecosystem services provided.

350 We then grouped the SARs according to the signs of the changes in the provision of the  
351 different ecosystem services. Because pairwise comparisons are easy to interpret and  
352 represent (Jopke et al., 2014), we followed a decision tree (depicted in Figure 2) making  
353 successive pairwise comparisons. First, we grouped the four ecosystem services into two  
354 indices, one representative of food production, being it the maximum between livestock  
355 production and crop production (Eq. [9]), and one representative of the other ecosystem  
356 services, being it the maximum between carbon sequestration and timber growth (Eq.  
357 [10]).

358

$$\Delta f_r = \max(\tilde{\Delta w}_{LP,r}, \tilde{\Delta w}_{CP,r}) \quad \text{Eq. (9)}$$

$$\Delta e_r = \max(\tilde{\Delta w}_{CS,r}, \tilde{\Delta w}_{TG,r}) \quad \text{Eq. (10)}$$

359

360 Second, we classified the SARs according to the combined sign of the two indices. If the  
361 combined sign was negative, then both ecosystem services composing the index had a  
362 negative change; if the combined sign was positive, at least one of the two ecosystem  
363 services composing the index had a positive change, and further investigation was  
364 necessary to identify which ecosystem service  $s$  had a positive change (see Figure 2).

365 If  $\Delta f_r > 0$  and  $\Delta e_r \leq 0$ , then the changes in carbon sequestration and timber growth were  
366 both negative (or null), so we explored the possible sign combinations of the changes in  
367 livestock production and crop production (they could be both positive or sign discordant).

368 If  $\Delta f \leq 0$  and  $\Delta e > 0$ , then the changes in livestock production and crop production were  
369 both negative (or null), so we explored the possible sign combinations of the changes in  
370 carbon sequestration and timber growth. If  $\Delta f > 0$  and  $\Delta e > 0$ , then we explored the  
371 possible sign combinations of the changes in livestock production and crop production  
372 and those of the changes in carbon sequestration and timber growth. If  $\Delta f \leq 0$  and  $\Delta e \leq 0$ ,  
373 none of the ecosystem services in the SAR increased.

### 374 *2.3.2 Analysis of the drivers of ecosystem services in the different groups of SARs*

375 For the analysis of the ecosystem service changes and their drivers in the different groups  
376 found in the SAR classification, for each group  $g$ , we calculated the variation in  
377 ecosystem services per unit of management area  $\Delta w_{s,g}$ , the normalized changes in  
378 ecosystem service  $\tilde{\Delta w}_{s,g}$  (with formulas, analogous to Eq.[7] and Eq.[8], reported in  
379 Table 1), the change in land use fractions  $\Delta \theta_{l,g}$ , and the change in pesticide expense in  
380 fodderland  $\Delta w_{PE,FOD,g}$  and cropland  $\Delta w_{PE,C,g}$  (formulaic expressions are given in Table  
381 1).

382

### 383 **3. Results**

384 The evolutionary algorithm modified the land covers and land uses in the SARs,  
385 improving livestock production by 20% on a national scale while ensuring no loss of  
386 other ecosystem services and no increase in total pesticide expense. Thus, the trade-offs  
387 between ecosystem services could be softened to a certain extent. The ecosystem services  
388 other than livestock production did not increase at the national level. The classification of  
389 the SARs based on changes in food production and other ecosystem services identified  
390 five groups of SARs exhibiting distinct patterns of change in the amounts of ecosystem  
391 services provided, which were due to the changes in land cover and land use invoked by  
392 the optimization procedure.

#### 393 **3.1 Exploring the joint changes in ecosystem services**

394 The five groups of SARs identified by the hierarchical analysis of  $\Delta f$  and  $\Delta e$  are shown  
395 in Figure 3. In Group 1, comprising 48% of the SARs, food production increased and the  
396 other ecosystem services decreased (or didn't change) ( $\Delta f > 0, \Delta e \leq 0$ ). In Group 2,  
397 comprising 24% of the SARs, food production decreased (or didn't change) and the other  
398 ecosystem services increased ( $\Delta f \leq 0, \Delta e > 0$ ). In Group 3, comprising 16% of the  
399 SARs, both food production and the other ecosystem services increased ( $\Delta f > 0, \Delta e >$   
400  $0$ ). In Group 4, comprising 4% of the SARs, at least one of the ecosystem service  
401 decreased and the other ecosystem remained constant, such that no ecosystem service  
402 increased. In Group 5, comprising 8% of the SARs, there was no change in any of the  
403 ecosystem services. Increases in ecosystem services in Groups 1, 2, and 3 compensated

404 for the losses of ecosystem services in Group 4. In Group 5, changes in land cover and  
405 land use were not possible. We explored the joint changes in the ecosystem services in  
406 Groups 1, 2, and 3 further (Figure 4).

407 In the SARs of Group 1, the changes in carbon sequestration and timber growth were  
408 negative, so we explored the joint changes in livestock production and crop production.  
409 The SARs of Group 1 fell into three sub-groups (Figure 4a): those in which livestock  
410 production increased and crop production decreased ( $\Delta lp_N > 0, \Delta cp_N \leq 0$ , Group 1.1),  
411 those in which livestock production decreased and crop production increased ( $\Delta lp_N \leq$   
412  $0, \Delta cp_N > 0$ , Group 1.2), and those in which both livestock production and crop  
413 production increased ( $\Delta lp_N > 0, \Delta cp_N > 0$ , Group 1.3).

414 In the SARs of Group 2, the changes in livestock production and crop production were  
415 negative, so we explored the joint changes in carbon sequestration and timber growth.  
416 The SARs of Group 2 fell into two groups (Figure 4b): those in which both carbon  
417 sequestration and timber growth increased ( $\Delta cs_N > 0, \Delta tg_N > 0$ , Group 2.1) and those in  
418 which carbon sequestration increased and timber growth decreased ( $\Delta cs_N > 0, \Delta tg_N \leq 0$ ,  
419 Group 2.2). We did not find SARs in which timber growth increased and carbon  
420 sequestration decreased.

421 In the SARs of Group 3, the changes in both food production and the other ecosystem  
422 services were positive, while we verified that carbon sequestration always increased and  
423 timber growth always decreased (results not shown). We explored the joint changes in  
424 livestock production and crop production. The SARs of Group 3 fell into three sub-  
425 groups, each characterised by an increase in carbon sequestration and a decrease in  
426 timber growth (Figure 4c): those in which livestock production increased and crop

427 production decreased (or didn't change) ( $\Delta lp_N > 0, \Delta cp_N \leq 0, \Delta cs_N > 0, \Delta tg_N < 0,$   
428 Group 3.1), those in which livestock production decreased (or didn't change) and crop  
429 production increased ( $\Delta lp_N \leq 0, \Delta cp_N > 0, \Delta cs_N > 0, \Delta tg_N < 0,$  Group 3.2), and those  
430 in which both livestock production and crop production increased ( $\Delta lp_N > 0, \Delta cp_N >$   
431  $0, \Delta cs_N > 0, \Delta tg_N < 0,$  Group 3.3).

### 432 **3.2 Analysis of the drivers**

433 We analysed the changes in the decision variables in the groups characterised by at least  
434 one positive change in one ecosystem service (i.e. Groups 1.1, 1.2, 1.3, 2.1, 2.2, 3.1, 3.2,  
435 3.3). The analysis is depicted in Figure 5.

436 The changes in land covers and pesticide expense within each group (Figure 5) revealed  
437 how the drivers changed the ecosystem services, resulting in trade-offs or synergies. In  
438 Group 1.1, livestock production increased because of expansion and intensification of  
439 fodderland, which came at the expense of all the other land covers, causing a decrease in  
440 all of the other ecosystem services. In Group 1.2, crop production increased because of  
441 expansion and intensification of cropland, which came at the expense of fodderland, non-  
442 permanent grassland, and forest, while there was a small expansion of permanent  
443 grassland. In Group 1.3, livestock and crop production increased because of expansion  
444 and intensification of fodderland and cropland, which provoked a large reduction in non-  
445 permanent grassland and forest, resulting in decreased carbon sequestration and timber  
446 growth; as in Group 1.2, there was a slight expansion of permanent grassland. In Group  
447 2.1, carbon sequestration and timber growth increased because of forest expansion (a  
448 common driver of those two ecosystem services). That group had little cropland and  
449 fodderland, so the expansion of forest came mostly at the expense of non-permanent and

450 permanent grasslands. In Group 2.2, carbon sequestration increased because of expansion  
451 of permanent grassland at the expense of a slight part of forest, cropland, and fodderland,  
452 which decreased the other ecosystem services. In Group 3.1, livestock production and  
453 carbon sequestration increased because of expansions of fodderland and permanent  
454 grassland. The fodderland was intensified, and permanent grassland was a common  
455 driver of the two increased ecosystem services. In Group 3.2, crop production and carbon  
456 sequestration increased because of a slight expansion and intensification of cropland and  
457 a large expansion of permanent grassland. The other land covers were reduced, causing  
458 decreases of the remaining ecosystem services. Group 3.3 was the only group in which  
459 three ecosystem services increased (livestock production, crop production, and carbon  
460 sequestration). In that group, permanent grassland was highly expanded, mostly at the  
461 expense of non-permanent grassland. Cropland and fodderland expanded only slightly  
462 but were much intensified.

463

#### 464 **4. Discussion**

465 We modelled the provision of ecosystem services to investigate how land cover and land  
466 use could be allocated in farming systems (identified as the SARs) so to enhance the  
467 synergies and soften the conflicts between livestock production and other ecosystem  
468 services. The results showed that a 20% increase in livestock production nationally could  
469 be achieved while maintaining other ecosystem services and without increasing total  
470 pesticide expense. That overall result included spatial variation across the country,  
471 meaning that for achieving a target at the national level, different land cover and land use  
472 allocations are required across SARs.

473 We found three groups of SARs within which at least one ecosystem service increased  
474 (Groups 1, 2, and 3), one small group of SARs where no ecosystem service increased and  
475 at least one decreased (Group 4) and one group of SARs where ecosystem services had  
476 no variation (Group 5). We deepened the analysis in groups 1, 2, and 3 (arriving to a  
477 further sub-division into a total of 8 groups). In Groups 4 and 5 the constraints were too  
478 restrictive that the optimization procedure couldn't increase pesticide expense or land  
479 cover fractions. The variation in the levels of ecosystem services revealed that not all  
480 ecosystem services could be increased within the same SAR. Driver analysis showed that  
481 some land covers were able to promote livestock production and other ecosystem services  
482 at the same time. Those results provided a quantitative picture of the trade-offs and  
483 synergies between ecosystem services that are linked to livestock production. By  
484 analysing the changes in the decision variables, we could infer contrasting land  
485 management strategies to soften the trade-offs and promote the synergies between  
486 livestock production and other ecosystem services.

#### 487 **4.1 Softening trade-offs**

488 Trade-offs emerged because of limited land availability (Anderson-Teixeira et al., 2012;  
489 Metzger et al., 2006) and the constraints on pesticide expense. Some land covers (i.e.  
490 cropland and forest) were good for some ecosystem services but not for livestock  
491 production (see Figure 1 and Table 2). That implies that the allocation of one land cover  
492 promotes one ecosystem service at the expense of another ecosystem service. Our results  
493 suggested two land management strategies for softening such trade-offs: intensification  
494 and spatial segregation of functions.

##### 495 *4.1.1 Intensification*



496 A strategy to increase food production while leaving space for other ecosystem services  
497 is to decrease and intensify the space dedicated to agriculture (Phalan et al., 2010). In  
498 some of the SARs in our analysis (Groups 3.1 and 3.3), grasslands was expanded while  
499 cropland or fodderland were reduced and intensified, promoting both food production and  
500 carbon sequestration. That strategy corresponds to land sparing (Green et al., 2005), as a  
501 more food-productive land cover was reduced and intensified to allow for the expansion  
502 of grassland, which provided other ecosystem services.

#### 503 *4.1.2 Spatial segregation of functions*

504 With the constraints imposed at the national level, it was possible to achieve some local  
505 loss of ecosystem services while compensating for those losses with gains in the same  
506 ecosystem services in other parts of the country (see Seppelt et al., 2013). That resulted in  
507 the intensification and arable expansion within some SARs (Group 1) and grassland and  
508 forest expansion within other SARs (Group 2). For a few SARs, there was a decrease in  
509 all ecosystem services. The spatial segregation of function allowed livestock production  
510 to be increased without losing other ecosystem services at the national level. Segregation  
511 has been a cost-effective way to increase both agricultural revenue and carbon  
512 sequestration in Eastern Europe (Ruijs et al., 2013). The spatial segregation between food  
513 production and other ecosystem services corresponds to a land sparing strategy at the  
514 national level, which has already been reported as a way to reconcile food production and  
515 biodiversity conservation (Teillard et al., 2016).

516 Such spatial segregation could be seen as a displacement phenomenon (Meyfroidt and  
517 Lambin, 2009). Our results included a displacement phenomenon across regions within  
518 the same country: the improvement of environmental conditions in one region (e.g. the

519 expansion of forest and grassland) was accompanied by the degradation of environmental  
520 conditions in another region. In our optimization model, the expansion of agriculture was  
521 constrained such that it occurred in SARs where a small amount of deforestation was  
522 possible. The constraint was in agreement with a principle of commodity crop expansion  
523 (Meyfroidt et al. 2014), which states that the accessibility of land determines agricultural  
524 expansion. Although it softened the trade-offs between livestock production and other  
525 ecosystem services, the spatial segregation of functions was not necessarily a positive  
526 outcome for all of the SARs, as SARs with higher intensification could support severe  
527 environmental pollution, which would have detrimental effects on biodiversity (Benton et  
528 al., 2003; Teillard et al., 2016). Thus, spatial segregation could lead to environmental  
529 inequalities (Larrère, 2017) between people living in regions with severe environmental  
530 degradation (due to the expansion and intensification of agriculture) and people living in  
531 regions with better environmental quality (due to the expansion of grassland and forest).

#### 532 **4.2 Promotion of land covers providing multiple services**

533 The increase of livestock production and carbon sequestration in the same SARs was  
534 associated with the expansion of permanent grassland. The results of the calibration  
535 procedure showed that both non-permanent grassland and permanent grassland increased  
536 livestock production and carbon sequestration, however permanent grassland was more  
537 efficient in carbon sequestration, thus more adapted for promoting the synergy between  
538 livestock production and carbon sequestration. The multifunctionality of permanent  
539 grassland (Hector et al., 1999; Soussana and Lemaire, 2014) was evident in Group 3.1  
540 and Group 3.3 (in total the 18% of the SARs), where both livestock production and  
541 carbon sequestration increased, and in Groups 1.2, 1.3, and 2.2 and 3.2 (together

542 constituting 46% of the SARs), even if the expansion of permanent grassland was not  
543 sufficient to provoke a local increase in livestock production. In Group 3.3 (7% of the  
544 SARs), the massive expansion of grassland did contribute to increased livestock  
545 production. Our results provide quantitative evidence supporting the results of other  
546 studies in which the expansion of grassland, rather than that of other land covers,  
547 benefited ecosystem services and biodiversity (Freibauer et al., 2004; Soussana and  
548 Lemaire, 2004; Princé et al. 2015). The expansion of grassland was an efficient strategy  
549 also because grassland does not require the use of pesticides and makes it possible to  
550 increase livestock production by respecting the constraints of non-increase in pesticide  
551 expense.

552 Past studies have highlighted the risks of overly intensified grassland: overstocking could  
553 cause excessive greenhouse gas emissions and ammonia production that would  
554 counterbalance the positive effect on carbon sequestration (Bouwman et al., 1997;  
555 Dobbie and Smith, 2003). Recent studies demonstrated that accurate management of  
556 grasslands (Soussana and Lemaire, 2014; Loucougaray et al., 2015) based on the fine-  
557 tuning of livestock densities can enhance the synergy between carbon sequestration and  
558 livestock production. Similar management options have been proposed to enhance the  
559 synergy between livestock grazing and biodiversity in grasslands (Tichit et al. 2005a,  
560 2005b; Enri et al., 2017). Our results provide further evidence of the multifunctionality of  
561 grassland by showing quantitatively how grassland promotes synergy between livestock  
562 production and other ecosystem services. The expansion of grassland for the provision of  
563 multiple ecosystem services can be seen as a land sharing strategy (Green et al., 2005).

564 The expansion of grassland, which is better than fodderland for carbon sequestration but  
565 inferior to fodderland for livestock production, was associated with an intensification of a  
566 reduced fodderland area. That relationship was visible in Groups 3.1 and 3.3, where the  
567 expansion of grassland and intensification of fodderland produced local net increases in  
568 carbon sequestration and livestock production, and also in Groups 1.1, 1.3, where  
569 fodderland was intensified. Those results are analogous to the results obtained by Lamb  
570 et al. (2016), who showed that forest expansion to mitigate the greenhouse gas emitted by  
571 agriculture in the U.K. required the intensification of arable land, which caused other  
572 environmental impacts.

573 Our results highlight the advantages of land covers that provide multiple ecosystem  
574 services. Forest provided carbon sequestration and timber growth, a synergy that  
575 indirectly involved livestock production by saving space that could be used to soften the  
576 trade-off between livestock production and other ecosystem services. Other studies  
577 showed that cropland can also be multifunctional by providing food for humans and feed  
578 for livestock, notably through the use of by-products (Van Zanten et al., 2016; Mottet et  
579 al., 2017). A high level of multifunctionality is also reported in mixed systems where  
580 crop production and livestock production are integrated (Herrero et al., 2010; Bonaudo et  
581 al. 2014; Dumont et al. 2013).

### 582 **4.3 Livestock and the land sparing–sharing debate**

583 The relationship between livestock production and other ecosystem services feeds into  
584 the debate on land sparing–sharing (Green et al., 2005; Phalan et al., 2011). In line with  
585 the recommendation of Kremen et al. (2015), we extended the land sparing–sharing  
586 debate to multiple ecosystem services. We found that livestock production goes beyond

587 the land sharing–sparing dichotomy. Its close linkage to grassland and fodderland  
588 generated a hybrid solution, which is illustrated in the SARs where fodderland was  
589 reduced and intensified (land sparing) in order to reap the benefits of grassland expansion  
590 (land sharing). Finally, our findings supported multi-scale land sparing (Fischer et al.,  
591 2014), with a reduction and intensification of cultivated land at the local level and a  
592 spatial segregation of food production and other ecosystem services at the national level.

#### 593 **4.4 Approach limitations and perspectives**

594 The model we developed is strongly based on data, therefore it is valid only in the range  
595 of data used for calibration of the parameters and it can be applied only if data are  
596 available all over the target study area. We considered only the production factors and the  
597 decision variables related to our research questions, therefore the results are driven by the  
598 choice of these variables. However we believe this is a first step to highlight some  
599 mechanisms related to strategies for softening trade-offs and enhancing synergies  
600 between livestock production and other ecosystem services. In the way it is formulated,  
601 the model can be easily extended. The Cobb-Douglas function has been already selected  
602 in other studies (e.g., Onofri et al., 2017) for its goodness of fit with data and simplicity at  
603 the same time. Upon data availability, other production factors can be easily included in  
604 the function, for example fertilizer input or more economic variables such as labour  
605 intensity. The modelling approach can be easily adapted to answering other research  
606 question. For example, the crop composition and association can be used as a lever to  
607 soften ecosystem services trade-offs. Last but not least, other optimization scenarios can  
608 be formulated for answering new research questions, for example other ecosystem

609 services (e.g., carbon sequestration) could be maximised posing constraints on the  
610 remaining.

## 611 **5. Conclusions**

612 Our results highlight trade-offs and synergies between livestock production and other  
613 ecosystem services. The main strategy to cope with the trade-offs involved land sparing  
614 at both the local and the national levels. The main strategy to enhance the synergies was  
615 based on the expansion of grasslands in order to benefit from the multifunctionality of  
616 that land cover type in terms of livestock production and carbon sequestration. We  
617 identified a large number of SARs (64% of the total) where grassland was expanded  
618 without provoking a local net increase in livestock production. In a small number of  
619 SARs (18% of the total), we identified a local net increase in both livestock production  
620 and carbon sequestration. Future policies to improve the provision of multiple ecosystem  
621 services should seek to expand multifunctional areas.

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630

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942

## 943 **A1 Appendix 1 – Scenario Constraints**

944 The constraints posed in the different SARs took into account the land suitability to crop  
945 or livestock and how that suitability varies across France. We based the land suitability  
946 on livestock type regions (Perrot et al. 2013; Fig. A1), each of which had specific  
947 constraints (Table A1). The livestock type regions and their corresponding identification  
948 codes were as follows:

- 949 • (0) Specialised crop areas with no livestock
- 950 • (1) Mixed crop-livestock in the Parisian basin
- 951 • (1.1) Mixed crop-livestock in the Aquitain basin, Rhône Alp, or Alsace, where  
952 livestock decreased more rapidly
- 953 • (2) Western intensive livestock (dairy areas where there are no alternatives to  
954 livestock)
- 955 • (2.1) Intensive piedmont areas (beef production areas where there is little or no  
956 alternative to livestock)
- 957 • (3) North-western grassland-based areas
- 958 • (4) North-eastern grassland-based areas (dairy tradition)
- 959 • (4.1) North Massif Central areas (beef tradition)
- 960 • (5) Causses (limestone plateaux) and southwest-hills pastoral areas

- 961 • (5.1) Mediterranean pastoral areas
- 962 • (6) Wet mountains of Franche-Comté and Vosges (with strong dairy
- 963 specialisation)
- 964 • (6.1) Wet mountains of Auvergne and Massif Central (with mixed dairy-beef
- 965 systems)
- 966 • (7) High mountains (Alps and Pyrenees)

967

968 We calibrated the parameters in the ranges given by the French data. Therefore, during  
 969 the optimization processes, we imposed constraints to prevent the values of the decision  
 970 variables from going out of those ranges. In each livestock region, we imposed for each  
 971 variable a minimum value  $m$  and a maximum value  $M$ . At the initialisation of the  
 972 optimization procedure, if the value of a variable in a SAR was below  $m$ , that value could  
 973 not decrease. Analogously, if the value was above  $M$ , it could not increase. If the value  
 974 was between  $m$  and  $M$ , it could increase or decrease within the range  $[m; M]$ . In general,  
 975 we made  $m$  and  $M$  equal to  $q^-$  and  $q^+$  (the 0.25 and 0.75 quantiles calculated from the  
 976 French data for all of the SARs of the livestock type area), respectively. Those constraints  
 977 prevented the values of the decision variables from going out of the range given by the  
 978 French data. In some cases, we included other, more restrictive, policy or biophysical  
 979 constraints. We defined constraints to prevent the reduction of forest, except in highly  
 980 productive areas (regions 0, 1, 1.1, 2, and 2.1) where a small decrease (down to 95% or  
 981 more of the starting value) in permanent grassland and forest would enable the expansion  
 982 of more intensive land covers. Forest expansion was not feasible in those highly

983 productive areas. In region 3, we did not allow permanent grassland or forest to decrease,  
984 nor did we allow cropland or fodderland to increase. In regions 4 and 4.1, we allowed  
985 slight increases (of up to 105% of the starting value) in cropland, fodderland, and the  
986 pesticide expenses for those land covers. Furthermore, in regions 4 and 4.1, we allowed  
987 the transformation of non-permanent grassland into permanent grassland. In regions 5  
988 and 5.1, we allowed no changes in cropland, fodderland, and the pesticide expenses for  
989 those two land covers. We allowed forest to be increased to up to 110% of the starting  
990 value in regions 5 and 5.1 and up to two-thirds of the management area in region 7. In  
991 regions 6 and 6.1, we allowed decreases in cropland and fodderland, and we allowed  
992 forest expansion to up to two-thirds of the management area.

993

995 Table 1. List of symbols and definitions.

Symbol	Unit	Mathematical definition	Description
<b>Basic elements</b>			
$R$	-		Set of the 709 SARs considered in France
$S$	-	$S = \{LP, CP, CS, TG\}$	Set of the ecosystem services
$M$	-	$M = \{PE\}$	Set of the environmental impact
$D$	-	$D = \{FOD, C, NPG, PG, F, p_{FOD}, p_C\}$	Set of the decision variables
$L$	-	$L = \{FOD, C, NPG, PG, F\}$	Set of the land cover fractions
$Z_l$	-		Set of the sub-fractions of the land cover $l$
$U$	-	$U = \{p_{FOD}, p_C, k\}$	Set of the land-use-related production factors
$C$	-	$C = \{P, T\}$	Set of the climate-related production factors
$G$	-		Set of the groups of SARs
$R_g$	-		Set of the SARs belonging to group $g$
$A_r$	ha		Management area of the SAR $r$
$w_{s,r}, \bar{w}_{s,r}, w_{s,r}^*$	-	Eq. (5)	Generic, initial, optimized value of the ecosystem service $s$ in the SAR $r$
$w_{m,r}, \bar{w}_{m,r}, w_{m,r}^*$	-		Generic, initial, optimized value of the environmental impact $m$ in the SAR $r$
$\theta_{d,r}, \bar{\theta}_{d,r}, \theta_{d,r}^*$	-		Generic, initial, optimized value of the decision variable $d$ in the SAR $r$
$\theta_{l,r}$	-		Generic value of the land cover fraction $l$ in the SAR $r$
$\theta_{l,z,r}$	-		Generic value of the sub-fraction $z$ of the land cover fraction $l$ in the SAR $r$
$\theta_{u,r}$	-		Generic value of land-use-related production factor $u$ in the SAR $r$
$\theta_{c,r}$	-		Generic value of climate-related production factor $c$ in the SAR $r$
$\Theta_{d,r}$	-		Set of the constraints posed on the decision variable $d$ in SAR $r$



## Ecosystem services and environmental impacts

$LP$	[Mcal yr <sup>-1</sup> ]	Annual livestock production
$CP$	[Mcal yr <sup>-1</sup> ]	Annual crop production
$CS$	[gC yr <sup>-1</sup> ]	Annual carbon sequestration
$TG$	[m <sup>3</sup> yr <sup>-1</sup> ]	Annual timber growth
$PE$	[€ yr <sup>-1</sup> ]	Annual pesticide expense

## Land cover fractions

$FOD$	fraction	Fraction of the management area occupied by fodderland
$C$	fraction	Fraction of the management area occupied by cropland
$NPG$	fraction	Fraction of the management area occupied by non-permanent grassland
$PG$	fraction	Fraction of the management area occupied by permanent grassland
$F$	fraction	Fraction of the management area occupied by forest

## Land cover sub-fraction

$PG_{(231)}$	fraction	Fraction of the permanent grassland occupied by <i>Pastures</i> (CLC 231)
$PG_{(321)}$	fraction	Fraction of the permanent grassland occupied by <i>Natural Grasslands</i> (CLC 321)
$F_{(311)}$	fraction	Fraction of the forest occupied by <i>Broad Leaved Forest</i> (CLC 311)
$F_{(312)}$	fraction	Fraction of the forest occupied by <i>Coniferous Forest</i> (CLC 312)
$F_{(313)}$	fraction	Fraction of the forest occupied by <i>Mixed Forest</i> (CLC 313)
$F_{(323)}$	fraction	Fraction of the forest occupied by <i>Sclerophyllous Vegetation</i> (CLC 323)
$F_{(324)}$	fraction	Fraction of the forest occupied by <i>Transitional Woodland-Shrub</i> (CLC 324)

## Land-use-related production factors

$p_{FOD}$	[€ ha <sup>-1</sup> yr <sup>-1</sup> ]	Annual pesticide expense per unit area of fodderland
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$p_C$	[€ ha <sup>-1</sup> yr <sup>-1</sup> ]	Annual pesticide expense per unit area of cropland
$k$	[Mcal]	Average energetic content of cultivated crop

### Climate-related production factors

$P$	[mm yr <sup>-1</sup> ]	Mean annual rainfall
$T$	[°C]	Mean annual temperature

### Cobb-Douglas function parameters

$\alpha_{s,l,z}$	-	Coefficient of the Cobb-Douglas function referred to ecosystem service $s$ and the sub-fraction $z$ of the land cover fraction $l$
$\gamma_{s,u,l,z}$	-	Exponent of the Cobb-Douglas function referred to ecosystem service $s$ , land-use-related production factor $u$ , and the sub-fraction $z$ of the land cover fraction $l$
$\gamma_{s,c,l,z}$	-	Exponent of the Cobb-Douglas function referred to ecosystem service $s$ , land-use-related production factor $c$ , and the sub-fraction $z$ of the land cover fraction $l$

### Parameters for the analysis of the results

$\Delta w_{s,r}$	-	Eq. (7)	Variation of ecosystem service $s$ per unit of management area in the SAR $r$ .
$\tilde{\Delta w}_{s,r}$	-	Eq. (8)	Normalized variation of ecosystem service $s$ per unit of management area in the SAR $r$ .
$\Delta f_r$	-	Eq. (9)	Index of change in food-related ecosystem services in the SAR $r$ .
$\Delta e_r$	-	Eq. (10)	Index of change in ecosystem services (other than food-related ecosystem services) in the SAR $r$ .
$\Delta w_{s,g}$	-	$\Delta w_{s,g} = \frac{\sum_{r \in R_g} \Delta w_{s,r}}{\sum_{r \in R_g} A_r}$	Variation of ecosystem service $s \in S$ per unit of management area in the group $g \in G$ .
$\tilde{\Delta w}_{s,g}$	-	$\tilde{\Delta w}_{s,g} = \frac{\Delta w_{s,g}}{\max_{g \in G} (abs(\Delta w_{s,g}))}$	Normalized variation of ecosystem service $s \in S$ per unit of management area in the group $g \in G$ .

$\Delta\theta_{l,g}$	Fraction	$\Delta\theta_{l,g} = \frac{\sum_{r \in R_g} ((\theta_{l,r}^* - \bar{\theta}_{l,r}) \cdot A_r)}{\sum_{r \in R_g} A_r}$	Change of the land cover fraction $l$ in the group $g$
$t_{PE,l,g}$	[€ m <sup>-2</sup> yr <sup>-1</sup> ]	$t_{PE,l,g} = \frac{\sum_{r \in R_g} (\theta_{p,l,r} \cdot \theta_{l,r} \cdot A_r)}{\sum_{r \in R_g} \theta_{l,r} \cdot A_r}$	Annual Pesticide expense per unit area of land cover fraction $l \in \{C, FOD\}$ in the group $g$
$\Delta t_{PE,l,g}$	[€ m <sup>-2</sup> yr <sup>-1</sup> ]	$t_{PE,l,g}^* - \bar{t}_{PE,l,g}$	Variation in Annual pesticide expense per unit area of land cover fraction $l \in \{C, FOD\}$ in the group $g$

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996 Table 2. Parameters (coefficients and exponents) of the Cobb-Douglas function used as a ecological production function for estimating the  
 997 ecosystem services provision (crop production, livestock production, carbon sequestration, and timber growth; see Eq. (6)) in a generic SAR. The  
 998 coefficient  $\alpha$  vary with ecosystem service and land cover. The exponents  $\gamma$  vary with ecosystem service, land cover, and production factors. The  
 999 symbol “-“ indicates that the production factor has no influence in the provision of a given ecosystem service for given land use and production  
 1000 factor. The production factors are  $p_d$  with  $d \in \{FOD, C\}$ , representing the pesticide expense per unit area in fodderland (FOD) or cropland (C) [ $\text{€ ha}^{-1}$   
 1001  $\text{yr}^{-1}$ ];  $R$ , representing the mean annual rainfall [ $\text{mm yr}^{-1}$ ], and  $T$ , representing mean annual temperature [ $^{\circ}\text{C}$ ].

Cobb-Douglas function parameters	$\alpha$	Exponents $\gamma$				
Production factors	-	$p$	$k$	$R$	$T$	
Crop production [Mcal] $R^2 = 0.987$						
Cropland	7.910	0.284	1.339	0.243	0.348	
Livestock production [Mcal] $R^2 = 0.889$						
Fodderland	188.293	0.381	-	0.342	0	
Non-permanent grassland	2.891	-	-	0.709	0	
Permanent grassland <sup>(1)</sup>	1.022	-	-	0.701	0	
Permanent grassland <sup>(2)</sup>	1.294	-	-	0.545	0	

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Carbon Sequestration [ $10^9$  gC yr<sup>-1</sup>] R<sup>2</sup> = 0.819

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	Cropland	0.059 <sup>(1)</sup>	-	-	0	0	
	Fodderland	0.051 <sup>(1)</sup>	-	-	0.001	0.001	
	Non-permanent grassland	1.131 <sup>(1)</sup>	-	-	0	0.450	
Permanent grassland <sup>(2)</sup>	(1)	1.933 <sup>(1)</sup>	-	-	0.002	0.453	
	(2)	1.724 <sup>(1)</sup>	-	-	0.001	0.454	
	(1)	4.015 <sup>(1)</sup>	-	-	0.004	0.460	
	(2)	2.884 <sup>(1)</sup>	-	-	0.004	0.480	
	Forest <sup>(3)</sup>	(3)	2.661 <sup>(1)</sup>	-	-	0.002	0.454
		(4)	2.591 <sup>(1)</sup>	-	-	0.001	0.262
		(5)	2.659 <sup>(1)</sup>	-	-	0.001	0.076

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Timber growth [m<sup>3</sup> yr<sup>-1</sup>] R<sup>2</sup> = 0.870

	Forest <sup>(3)</sup>	(1)	0.501 <sup>(1)</sup>	-	-	0.321	0
		(2)	0.103 <sup>(1)</sup>	-	-	0.493	0.387

1002 <sup>(1)</sup> To be multiplied by 10<sup>4</sup>

1003 <sup>(2)</sup> Divided into sub-fractions: (1) *Pastures* (CLC 231); (2) *Natural Grasslands* (CLC 321)

1004 <sup>(3)</sup> Divided into sub-fractions: (1) *Broad Leaved Forests* (CLC 311); (2) *Coniferous Forest* (CLC 312); (3) *Mixed Forest* (CLC 313),  
1005 *Sclerophyllous Vegetation* (CLC 323); (4) *Transitional Woodland-Shrub* (CLC 324)  
1006  
1007 Table A1. Ranges of variation in the land cover fractions (cropland  $C$ , fodderland  $FOD$ , non-permanent grassland  $NPG$ , permanent grassland  $PG$ ,  
1008 and forest  $F$ ) and pesticide expense for cropland  $p_C$  and fodderland  $p_{FOD}$  allowed in the SARs of the different livestock type regions during the  
1009 Optimization process. The initial variables in the SARs are indicated by  $\bar{C}, \bar{FOD}, \bar{NPG}, \bar{PG}, \bar{F}, \bar{p}_C$ , and  $\bar{p}_{FOD}$ .

Region	$C$	$FOD$	$NPG$	$PG$	$F$	$P_{C,0}$	$p_{FOD,0}$
0	$[q; q^+]$	$[q; q^+]$	$[q; q^+]$	$[0.95\bar{PG}; q^+]$	$[0.95\bar{F}; \bar{F}]$	$[q; q^+]$	$[q; q^+]$
1	$[q; q^+]$	$[q; q^+]$	$[q; q^+]$	$[0.95\bar{PG}; q^+]$	$[0.95\bar{F}; \bar{F}]$	$[q; q^+]$	$[q; q^+]$
1.1	$[q; q^+]$	$[q; q^+]$	$[q; q^+]$	$[0.95\bar{PG}; q^+]$	$[0.95\bar{F}; \bar{F}]$	$[q; q^+]$	$[q; q^+]$
2	$[q; q^+]$	$[q; q^+]$	$[0.5\bar{NPG}; q^+]$	$[0.95\bar{PG}; q^+]$	$[0.95\bar{F}; \bar{F}]$	$[q; q^+]$	$[q; q^+]$
2.1	$[q; q^+]$	$[q; q^+]$	$[0.2\bar{NPG}; q^+]$	$[0.95\bar{PG}; q^+]$	$[0.95\bar{F}; \bar{F}]$	$[q; q^+]$	$[q; q^+]$
3	$[q; \bar{C}]$	$[q; \bar{FOD}]$	$[q; q^+]$	$[\bar{PG}; q^+]$	-	$[q; \bar{p}_C]$	$[q; \bar{p}_{FOD}]$

4	$[q^-; 1.05\bar{C}]$	$[q^-; 1.05\bar{FOD}]$	$[q^-; q^+]*$	$[\bar{P}G; q^+]$	-	$[q^-; 1.05\bar{p}_C]$	$[q^-; 1.05\bar{p}_{FOD}]$
4.1	$[q^-; 1.05\bar{C}]$	$[q^-; 1.05\bar{FOD}]$	$[q^-; q^+]*$	$[\bar{P}G; q^+]$	-	$[q^-; 1.05\bar{p}_C]$	$[q^-; 1.05\bar{p}_{FOD}]$
5	-	-	$[q^-; \bar{NPG}]^*$	$[q^-; q^+]**$	$[\bar{F}; 1.10\bar{F}]$	$[q^-; \bar{p}_C]$	$[q^-; \bar{p}_{FOD}]$
5.1	-	-	$[q^-; \bar{NPG}]^*$	$[q^-; q^+]**$	$[\bar{F}; 1.10\bar{F}]$	$[q^-; \bar{p}_C]$	$[q^-; \bar{p}_{FOD}]$
6	$[q^-; \bar{C}]$	$[q^-; \bar{FOD}]$	$[q^-; q^+]*$	$[q^-; q^+]**$	$[\bar{F}; 0.67]$	$[q^-; \bar{p}_C]$	$[q^-; \bar{p}_{FOD}]$
6.1	$[q^-; \bar{C}]$	$[q^-; \bar{FOD}]$	$[q^-; q^+]*$	$[q^-; q^+]**$	$[\bar{F}; 0.67]$	$[q^-; \bar{p}_C]$	$[q^-; \bar{p}_{FOD}]$
7	-	-	$[q^-; \bar{NPG}]^*$	$[q^-; q^+]**$	$[\bar{F}; 0.67]$	$[q^-; \bar{p}_C]$	$[q^-; \bar{p}_{FOD}]$

1010  $q^-$  represents the 0.25 quantile of the variable measured within all the SARs belonging to the livestock type region.

1011  $q^+$  represents the 0.75 quantile of the variable measured within all the SARs belonging to the livestock type region.

1012 - indicates that the variable cannot change.

1013 \* indicates that the land cover type can only be transformed into permanent grassland.

1014 \*\* indicates that the land cover type can only be transformed into forest.

1015

1016 Table A2. Ranges of variation of the different areas and pesticide expenses in the different livestock typology region. The  
 1017 ranges are expressed as [-x; +y] where x and y are percentages of the initial total areas (of cropland, fodderland, non-  
 1018 permanent grassland, permanent grassland, and forest) in each livestock typology region and percentage of the total pesticide  
 1019 expense in cropland and fodderland. The minimum (maximum) total pesticide expense allowed was obtained by multiplying  
 1020 the minimum (maximum) cropland or fodderland area allowed by the minimum (maximum) pesticide expense allowed in  
 1021 cropland or fodderland.

Region	Percentage of SARs	Cropland	Fodderland	Non Permanent Grassland	Permanent Grassland	Forest	Pesticide expense in cropland	Pesticide expense in fodderland
	[%]	Range of variation	Range of variation	Range of variation	Range of variation	Range of variation	Range of variation	Range of variation
0	24.5	[-37; +29]	[-85; +62]	[-79; +80]	[-5; +67]	[-5; +0]	[-54; +44]	[-93; +105]
1	15.7	[-34; +27]	[-69; +41%]	[-61; 85]	[-5; +51]	[-5; +0]	[-50; +38]	[-79; +82]
1.1	10.0	[-27; +57]	[-58; +76]	[-78; 34]	[-5; +55]	[-5; +0]	[-31; +117]	[-72; +112]
2	6.6	[-76; +92]	[-82; +5]	[-80; +10]	[-5; +135]	[-5; +0]	[-79; +120]	[-83; +20]



2.1	5.6	[-32; +646]	[-33; +355]	[-80; +81]	[-5; +10]	[-5; +0]	[-46; +757]	[-38; +441]
3	4.2	[-44; +0]	[-47; +0]	[-78; +47]	[-0; +40]	[-0; +0]	[-50; +0]	[-50; +0]
4	5.4	[-64; +5]	[-67; +5]	[-1; +227]	[-0; 50]	[-0; +0]	[-69; +10]	[-79; +10]
4.1	5.4	[-48; +5]	[-40; +5]	[-32; +22]	[-0; +14]	[-0; +0]	[-56; +10]	[-66; +10]
5	3.1	[-0; +0]	[-0; +0]	[-35; +0]	[-59; +26]	[-0; +10]	[-30; +0]	[-50; +0]
5.1	5.9	[-0; +0]	[-0; +0]	[-44; +0]	[-51; +74]	[-0; +10]	[-27; +0]	[-15; +0]
6	2.3	[-79; +0]	[-71; +0]	[-58; +199]	[-32; +97]	[-0; +8]	[-81; +0]	[-78; +0]
6.1	6.2	[-81; +0]	[-84; +0]	[-79; +35]	[-50; +39]	[-0; +35]	[-86; +0]	[-89; +0]
7	5.5	[-0; +0]	[-0; +0]	[-93; +0]	[-24; +45]	[-0; +2]	[-8; +0]	[-25; +0]
Total	100	[-41; +39]	[-66; +29]	[-65; +43]	[-16; +46]	[-2; +5]	[-53; +54]	[-72; +48]

1022

1023 **Figure captions**

1024 Figure 1. Interactions between model inputs (rounded rectangles) and outputs (non-rounded  
1025 rectangles). The inputs can be decision variables (grey rounded rectangles), intermediary  
1026 variables (rounded rectangles with an arrow coming in), or production factors kept constant  
1027 during the optimization procedure (rounded rectangles without an arrow coming in). The strength  
1028 of the relationship was tested with the calibration procedure.

1029

1030 Figure 2. Decision tree for the analysis of the variation in ecosystem services.  $\Delta f$  represents the  
1031 maximum between the normalised livestock production and the normalised crop production.  $\Delta e$   
1032 represents the maximum between the normalised carbon sequestration and the normalised timber  
1033 growth.

1034

1035 Figure 3. Joint changes in aggregated indices of ecosystem services in different SARs. The  
1036 indices represent food production and other ecosystem services. The different groups of SARs  
1037 based on the changes in ecosystem services are identified on the map: Group 1, increase in food  
1038 production and decrease (or no change) in other ecosystem services; Group 2, decrease (or no  
1039 change) in food production and decrease in other ecosystem services; Group 3, increase in both  
1040 food production and other ecosystem services; Group 4, decrease or no change in all ecosystem  
1041 services (without absence of change in all the ecosystem services); Group 5, no changes in any  
1042 ecosystem services.

1043

1044

1045 Figure 4. Joint changes in the ecosystem services in Groups 1, 2, and 3 identified in the first  
1046 hierarchical level of the analysis (depicted in Figure 3). Panel (a) represents jointly the  
1047 normalised changes in livestock production and crop production (with the changes in carbon  
1048 sequestration and timber growth both negative). Panel (b) represents jointly the normalised  
1049 changes in carbon sequestration and timber growth (with the changes in livestock production and  
1050 crop production both negative). Panel (c) represents jointly the normalised changes in livestock  
1051 production and crop production (with the changes in timber growth negative and carbon  
1052 sequestration positive).

1053

1054 Figure 5. Statistics of the results obtained for each group  $g$  (represented in each row). The first  
1055 column gives the number of SARs and total management area composing the group. The second  
1056 column gives the normalised changes in ecosystem services per unit area ( $\tilde{\Delta w}_{s,g}$  as defined in  
1057 Table 1), i.e., livestock production ( $LP$ ), crop production ( $CP$ ), carbon sequestration ( $CS$ ), and  
1058 timber growth ( $TG$ ). The third column gives the change in land cover ( $\Delta\theta_{l,g}$  as defined in Table  
1059 1), i.e. fodderland ( $FOD$ ), cropland ( $C$ ), non-permanent grassland ( $NPG$ ), permanent grassland  
1060 ( $PG$ ), and forest ( $F$ ) as a fraction of total management area of the group. The fourth column gives  
1061 the change in pesticide expense per unit area ( $\Delta t_{PE,l,g}$  as defined in Table 1) of cropland ( $C$ ) or  
1062 fodderland ( $FOD$ ).

1063

1064 Figure A1. Regions in France characterised by different livestock Systems according to Perrot et  
1065 al. (2013)