Land sharing strategies for addressing the trade-off between carbon storage and crop production in France

Yong Shi, Corentin Pinsard, Francesco Accatino

Addressing the trade-off between crop production and carbon storage at the country scale with land-use optimisation scenarios

Yong Shi[1], Corentin Pinsard[1], Francesco Accatino[1]

[1] UMR SADAPT, INRAE, AgroParisTech, Université Paris-Saclay, 75005, Paris, France

Abstract (150-250 words)

Managing land for trade-off between crop production (CP) and carbon storage (CS) is important for facing the increased need of food and of creating carbon sinks. We studied land-use-based strategies for softening such trade-off, with a particular attention to the role of intensification. We calibrated a statistical model linking land cover, land use, climatic and biophysical variables to CP and CS in France at the resolution of 10 km x 10 km. We developed four optimization scenarios: maximization at the French scale of CS (scenario 1), of CP (2), joint maximization of CS and CP without (3) and with (4) minimization of total energy input. Results of the mono-objective scenarios ((1) and (2)) enhanced one ecosystem services while decreasing the other; in scenario (3) both ecosystem services could be increased at the same time (+2.1% for CS and +9.6% for CP) with a land sharing approach (decrease and intensification of annual crops with an increase of forest); in scenario (4) the minimization of energy input caused a lower increase in both ecosystem services (only +1% for CS and +1.5% for CP), however the joint increase could be obtained with an expansion of heterogeneous agricultural land (land sharing approach). Comparing optimization scenarios with different number of objectives made it possible to discuss the role of each objectives. The result of scenario (4) was the most realistic and highlighted the importance of heterogeneous agricultural land (e.g., mixed-crop agriculture, agroforestry, associations between permanent and annual crops) and practices for enhancing soil carbon storage.

Key words: ecosystem services; land sparing; land sharing; modelling; intensification; heterogeneous agricultural land

Introduction

The expansion and intensification of agricultural land in the last decades was driven by an increasing world population' s food demand (Foley et al. 2011) and was one of the main causes of natural resources loss (Butchart et al. 2010). More and more awareness raised about the importance of enhancing carbon sequestration and preserving the carbon stored in the soils (Smith 2016). Soils can act as carbon sinks offsetting a part of the fossil fuels emissions reducing the atmospheric concentration of CO_2 (Kell 2012; Lal et al. 2015), therefore contrasting the effects of global warming (IPCC 2018). Soil carbon sequestration has been set in the agenda of a number of policies and directives (see for example the Biodiversity Strategy by the European Commission for 2030 [EC, 2020]). During the COP21 in 2015 (when the Paris agreement was reached), the French government launched the *4p1000 initiative* ("4 per 1000: Soils for Food Security and Climate") for promoting the engagement in increasing soil organic carbon at a rate of 0.4% each year (Chabbi et al. 2017; Kon Kam King et al. 2018; Soussana et al. 2019; Rumpel et al. 2020). Given the likelihood of increasing food demand and of more affluent diets in the next decades (Godfray et al. 2010; Foley et al. 2011), it is important to conciliate the need for food production with the need of preserving carbon storage and halting the loss of the already stored soil carbon in grasslands and forests, as well as with other ecosystem services, which are the public goods delivered by nature (Daily 1997).

For conciliating carbon storage and crop production, it is important to consider conflicting land uses. Land is a scarce resource and soil is one of the major providers of ecosystem services (Autret et al. 2016). The increase in a land cover leads to a decrease in other land covers, along with all the ecosystem services associated to them (Metzger et al. 2006). The land sparing/land sharing debate (Green et al. 2005; Phalan et al. 2011) provides a frame of analysis based on the tension between intensification and expansion of agricultural land. The land sparing approach consists of intensifying agricultural land so that it can be reduced and some land can be spared for nature conservation. The land sharing approach consists of extending agricultural land and, at the same time, using more nature-inclusive practices. Although this framework was generated around the conflict between agricultural production and biodiversity, it is well adapted also to the conflict between agricultural production and ecosystem services (Kremen and Ostfeld 2005; Accatino et al. 2019), and carbon storage in particular.

Modelling techniques can help in quantitatively characterizing the trade-off between agricultural land and ecosystem services, and might suggest strategies to tackle these trade-offs. The study of (Johnson et al. 2014) explored the possibility to increase crop production at the global scale without harming carbon storage. The solution proposed by Johnson et al. (2014) was a selective extensification, consisting of expanding agriculture in particular selected place that minimizes carbon loss from land conversion. However, in this study no intensification was considered in the model. Other studies focused on trade-offs between crop production and other ecosystem services. (Deguines et al. 2014) investigated the trade-off between agricultural intensification and crop pollination services according to the empirical evidence of 54 major crops in France produced over the past two decades. Shin-ichiro et al. (2019) studied the role of wetlands by exploring the trade-off between crop production and water quality.

A regard to the ecosystem service modelling literature reveals the importance of optimization techniques in addressing trade-offs between ecosystem services, biodiversity and agricultural production. Optimization makes it possible to systematically explore the combination of values of certain variables in order to find target solutions that maximize or minimize certain desired objectives (Seppelt et al. 2013). Accatino et al. (2019) optimize one ecosystem service putting constraints of no-loss on other ecosystem services, (Setälä et al. 2014) explored trade-off relationship between ecosystem services in urban and agricultural soils. Some studies focus on optimizing more objectives at the same time. Pareto fronts are important tools for showing possibility frontiers (Castelletti et al. 2010; Groot et al. 2018): the shown solutions for which one objective cannot be improved without worsening another. Studies in the literature have explored multi-objective optimization problems for studying trade-offs among ecosystem services (Li et al. 2013; Tóth et al. 2013; Schroder et al. 2016; Groot et al. 2018).

So far, few studies addressed the role of intensification in the trade-offs between carbon storage and agricultural production. Teillard et al. (2017) generated Pareto frontiers for investigating the role of agricultural intensification, extensification, and re-allocation in the conflict between agricultural production and biodiversity. They found that re-allocating energy input in agriculture is an avenue for improving biodiversity without reducing agricultural production. We believe that optimization scenarios can shed light on land use strategies to tackle trade-off, on the role of intensification, and can provide land sparing or land sharing strategies as outcomes. The role of the number of objectives to consider in an optimization problem was not addressed. Adding or removing objectives in the optimization problem can have important consequences on the results obtained (Bradford and D'Amato 2012). We believe that comparing different scenarios including or removing certain objectives can help in understanding the importance of that objective in the overall trade-off.

In this study we aimed at exploring the trade-off between crop production and carbon storage at the country scale, considering France as a case study. In particular, we explored the role of intensification and extensification for enhancing both the ecosystem services considered. For doing that we built a model calibrated with data and run optimization scenarios. Objectives involved are crop production and carbon storage (to maximize) and energy input (to minimize), being energy input a proxy of agricultural intensification. Scenarios are designed with different number objectives in order to better understand the trade-off between crop production and carbon storage, as well as the role of agricultural intensification. For each optimized solution we discussed the land use configuration to achieve that. The results contribute to provide useful considerations for the land sparing and land sharing debate, as well as some direction for policy-making strategies and for future model development.

Methods

We performed a series of optimization-based scenarios, using a model that links land cover, land use, and climate variables to the provision of two ecosystem services: crop production and carbon storage.

Model definition

The rationale of the model, which follows Accatino et al. (2019), is depicted in Figure 1. We gridded the studied area (metropolitan France) into 10 km ×10 km squares. In total 5110 land units were obtained, being them entire squares or smaller land units, where the cells of the grid intersected the border of France. Each land unit was assigned a set of variables and parameters. The management area S [ha] was defined as the land occupied by annual crops, permanent crops, heterogeneous agricultural land, grassland (either permanent or temporary), or forest. We considered these typologies of land covers as they are the most involved in managing the trade-offs between crop production and carbon storage, ranging from land covers mostly dedicated to crop production (*i.e.*, annual crops) to land covers mostly dedicated to carbon storage (*i.e.*, grassland and forest). Heterogeneous agricultural land refers to the definition given by the Corine Land Cover classification (EEA 2013), consisting in areas of annual crops associated with permanent crops, agro-forestry, landscapes in which crops and pastures are intimately mixed with natural vegetation. For each land unit, we defined the fraction ϕ [adimensional] of the management area S occupied by these land covers, namely ϕ_A (annual crops), ϕ_P (permanent crops), ϕ_H (heterogeneous agricultural land), ϕ_G (grassland), ϕ_F (forest). Being fractions, these variables range between 0 and 1 and must always sum up to 1 for each land unit. As a land use variable, we considered the energy input θ_E [MJ/ha] and water input θ_W [m^3] for agricultural production. These variables can be considered proxies of agricultural intensification (Pellegrini and Fernández 2018). As climate variables, we considered the total annual precipitation ϑ_R and the annual average temperature ϑ_T. We also consider, as a biophysical variable the organic matter in the topsoil ϑ_O.

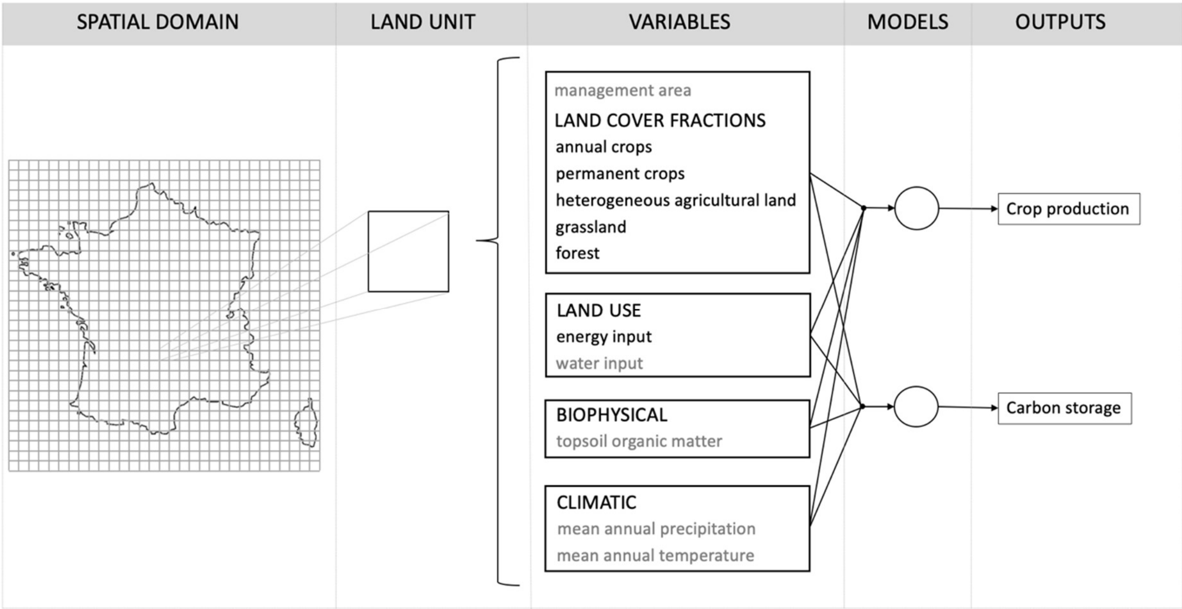

Figure 1 – Structure of the ecosystem service models. The spatial domain is the metropolitan France, the land unit is a square of 10 km x 10 km (the grid in the figure is only symbolic but not in scale), in case of land units intersecting with the border of the spatial domain, only the intersection area is considered. Concerning the variables, the semantic groups of variables are written in upper case and variables are written in lower case. Decision variables are written in black and non-decision variables (kept constant during the optimization process) are written in gray. Models elaborate the variables to give, at the scale of each land unit, the two ecosystem services considered: crop production and carbon storage.

The ecosystem services considered are crop production E_{CP} [tons dry matter. yr^{-1}] and carbon storage E_{CS} [tonC.ha^{-1}]. Crop production corresponds to the harvested production of food, textile, and energy crops. Carbon storage corresponds to the estimate of above- and below-ground carbon stored in living plant material. Although the storage of carbon is a dynamic process (carbon stored is a function of organic carbon inputs and biophysical conditions) (Ellert et al. 2001; Virto et al. 2012), by assumption, we considered carbon storage as at equilibrium (constant), and that the value, a characteristic of a given land cover with actual land use and management practices.

Model variables and outputs are linked by means of a statistical relationship. We chose that the provision of an ecosystem service $k \in \{CP, CS\}$ in a land unit *j*, indicated with $E_{k,j}$, is given by the sum of the contribution of each single land cover in equation (1):

$$E_{k,j} = S_j \cdot \sum_{l \in L} \phi_{l,j} \cdot f_{k,j}(\theta_E, \theta_W, \vartheta_R, \vartheta_T, \vartheta_O) \quad (1)$$

Where $L = \{A, P, H, G, F\}$ is the set of all land uses and $\phi_{l,j}$ is the fraction of land cover *l* of region *j*. The function $f_{k,l}(\cdot)$ represents the influence of land use, climate and biophysical conditions on the contribution of land use *l* to the ecosystem service *k*. Following Accatino et al. (2019) we chose a Cobb-Douglas function, which is shown in equation (2):

$$f_{k,l}(\theta_E, \theta_W, \vartheta_R, \vartheta_T, \vartheta_O) = \alpha_{k,l} \cdot \theta_{E,j}^{\gamma_{E,k,l}} \cdot \theta_{W,j}^{\gamma_{W,k,l}} \cdot \vartheta_{R,j}^{\gamma_{R,k,l}} \cdot \vartheta_{T,j}^{\gamma_{T,k,l}} \cdot \vartheta_{O,j}^{\gamma_{O,k,l}} \quad (2)$$

Where the coefficient $\alpha_{k,l}$ is characteristic of the ecosystem service *k* and of the land cover *l* and is representative of the contribution of the land cover in the provision of the ecosystem service. The exponents $\gamma_{i,k,l}$ are characteristic of the land use, climate variable or biophysical variable $i \in \{E, W, R, T, O\}$ for the ecosystem service *k* and the land cover *l*. The Cobb-Douglas function corresponds to a weighted product of factors and allows limited substitutability between them (in contract to the linear function that allows complete substitutability) (Grammatikopoulou et al. 2020; Zhang et al. 2020).

Optimization scenarios

The model described by equations (1) and (2) is used for running optimization scenarios. Within an optimization scenario, one or more objective to maximize or minimize are defined; then, starting from an initial configuration, some variables (hereafter called "decision variables") are systematically changed in order to find the optimal solutions. We chose that the decision variables were the land cover fractions ($\phi_{A,j}, \phi_{P,j}, \phi_{H,j}, \phi_{G,j}, \phi_{F,j}$) in each land unit and the energy input $\theta_{E,j}$ in each cell *j*. The variables that were not chosen as decision variables were kept constant along the optimization-based scenarios and were treated as parameters. The management area S_j of each land unit was kept constant and the land cover fraction were imposed to always sum to 1 while they were systematically changed.

We designed four optimization scenarios differing for the objective optimized and the number of objectives optimized (Table 1), the scenarios refer to the whole France, so they refer to the sum of the total carbon storage, crop production, and energy input over all the land units (J indicates the set of all the land units):

- Scenario 1 consisted of a mono-objective optimization that maximized the total carbon storage in the whole France,

$$max\left(\sum_{j \in J} E_{CS,j}\right) \tag{3}$$

- Scenario 2 consisted of a mono-objective optimization that maximized the total crop production in the whole France,

$$max\left(\sum_{j \in J} E_{CP,j}\right) \tag{4}$$

- Scenario 3 consisted of a bi-objective optimization that maximized at the same time the total carbon storage and the total crop production in the whole France,

$$\begin{cases} max\left(\sum_{j\in J} E_{CS,j}\right) \\ max\left(\sum_{j\in J} E_{CP,j}\right) \end{cases} \tag{5}$$

- Scenario 4 consisted of a triple-objective optimization that maximized at the same time the total carbon storage and the total crop production, while minimizing energy input in the whole France,

$$\begin{cases} max\left(\sum_{j\in J} E_{CS,j}\right) \\ max\left(\sum_{j\in J} E_{CP,j}\right) \\ min\left(\sum_{j\in J} \theta_{E,j}\right) \end{cases} \tag{6}$$

The optimization-based scenarios' output solutions could be regarded as a response of the land use and land cover to the corresponding objective functions. The obtained near-optimal solutions of the different scenarios could help explore the trade-off between crop production and carbon storage as well as the role of intensification in tackling the trade-off. Comparing scenarios 1 and 2 with scenario 3 and scenario 4 will show the role of adding objectives. Comparing scenario 3 with scenario 4 will highlight the role of intensification. For all the scenarios, not only it is interesting to investigate the values of the optimized objectives, but also to examinate how land cover and intensification decision variables are changed in order to attain the optimal solutions. We examined how land covers and energy inputs were changed at the aggregated level (averaged across all the land units) and at the level of each land unit. The optimization process could be regarded as an evolutionary process of solutions, which starts from a given initial configuration and gets to an optimized configuration. The initial configuration in this study is the one given by the data.

Table 1 – Overview of the optimization scenarios and of the objectives to be maximized or minimized. Scenarios are numbered from 1 to 4 and Vs indicate that the objective is accounted for.

Scenario	Objectives		
	Maximize carbon storage	Maximize crop production	Minimize energy input
1	V		
2		V	
3	V	V	
4	V	V	V

Constraints

During the optimization processes envisaged in all the scenarios, the decision variables are systematically changed by an evolutionary algorithm in order to find the optimal solution(s). However, not all changes in the variables could be possible. In addition to the constraints due to variable definitions (land cover fraction ranging between 0 and 1 and always summing to 1), we decided to assign another constraint imposing that decision variables could not change beyond -20% and +20% of their initial values. The reason behind this choice was twofold. Firstly, we did not want decision variables to go out of the range used for calibration. Being the model statistic and based on data, we decided not to explore solutions out of the validity domain. Secondly, we did not want to create revolutionary changes in land cover and land use, but to explore solutions around the current state, which could be potentially attainable in a time horizon of 10-20 years. With this constraint, the aim of the optimization scenarios was not to find the real optimized solutions, but to explore the strategies to follow in order to optimize objectives, while staying close to the current configuration.

Initialization and optimization procedure

The optimization problems corresponding to the scenarios presented belong to a class of large-scale nonlinear programming problems. For each scenario, there are 30660 decision variables to optimize (6 decision variables multiplied by 5110 land units) subject to constraints, therefore the current optimization solvers such as Lingo, Cplex, Gruobi cannot solve this problem (Anand et al. 2017). We used an evolutionary algorithm approach: for the mono-objective scenarios (scenarios 1 and 2) we applied Genetic Algorithm where the fitness function was the objective to maximize; for the multi-objective scenarios (scenarios 3 and 4), we used NSGAII with the package MOEA (Hadka 2015). Evolutionary algorithms do not generally find optimal values, but they can effectively explore the space of solutions. Finding the exact best solution was not the intention of this work. Through near-optimal solutions, it was possible to analyze how decision variables changed towards the achievement of the desired optimization targets as well as trade-offs and synergies among objectives. NSGAII can effectively solve non-convex problems and deals with complicated constraints; it has been widely used for addressing land cover and land use optimization, such as in Shaygan et al. (2013), Song and Chen (2018), and Gao et al. (2020). The optimization algorithm was implemented in Java with the Ubuntu 18.04 LTS.

Data and model calibration

For calibrating and initializing the model, data were considered for both model inputs (management areas, land cover fractions, energy and water input) and for model outputs (carbon storage and crop production). The management areas and the land cover fractions in each land unit were computed from the Corine Land Cover dataset for the year 2012 (EEA2013). Within each land unit, the number of pixels (100 m x 100 m) of each relevant Corine Land Cover category was re-classified in the land cover categories considered in this study (the correspondence between categories is given in Table 1 located in the Supplementary material). Energy input data corresponds to the input for producing agricultural goods (including labour, machinery, fertilisers and irrigation) [MJ.ha^{-1}] with data from years 2003 to 2005 (Commission of the European Union. Joint Research Centre. 2015). The water input corresponds to the water abstraction for agricultural use, averages for the years 2008 to 2012 [m^3](Maes et al. 2015). Topsoil organic matter content comes from the EFSA spatial data set version 1.1 (Hiederer et al. 2012). Harvested production from crops corresponds to the sum of the harvested production for food, feed, fiber, and fuel for the year 2011 (Maes et al. 2015). Finally, carbon storage is an estimated of the above and below-ground carbon in living material, coming from the CDIAC, using a global vegetation distribution for the year 2000 (European commission et al. 2011).

Once input and output data were available for each land unit, the parameter estimation was done with an evolutionary technique. Parameters $\alpha_{k,l}$ and $\gamma_{i,k,l}$ (for each ecosystem service k, land use or climate variable i and land cover l) were estimated to that the sum over all land units of the difference between modelled ecosystem services and data was minimize. The algorithm was super-visioned in order to avoid unrealistic parameter values. The R^2 values for crop production was 0.91 and for carbon storage was 0.67, both of which were acceptable (since values were greater than 0.5) for prediction of the two ecosystem services provisions. The detailed values of the parameters, including the coefficients and exponents, were summarized in Table 2.

Table 2 - The Cobb-Douglas function parameters

	α	Exponents γ				
		Land use, climate and biophysical variables				
		Energy input	Water input	Mean annual precipitation	Mean annual temperature	Topsoil organic matter
Crop production [tons dry matter.yr^{-1}]						
Annual crops	$5.06 \cdot 10^{-3}$	0.40	0.03	0.20	0.00	0.06
Permanent crops	$1.00 \cdot 10^{-5}$	0.00	1.99	0.00	0.00	0.00
Heterogeneous agr. land	$4.96 \cdot 10^{-3}$	0.30	0.12	0.26	0.09	0.16
Carbon storage [tonsC.ha^{-1}]						
Annual crops	$1.00 \cdot 10^{-4}$	-1.43	1.94	0.46	1.95	0.01
Permanent crops	$2.00 \cdot 10^{-4}$	0.32	0.00	0.00	0.00	0.001
Heterogeneous agr. land	$2.00 \cdot 10^{-4}$	0.44	0.00	0.42	0.00	0.47
Grassland	$5.20 \cdot 10^{-3}$	0.47	0.10	0.00	0.00	0.02
Forest	$1.02 \cdot 10^{-2}$	-0.11	0.00	0.01	0.00	0.02

Results

Optimized objectives

The results of the four optimization scenarios are represented together in the same plot in order to allow comparison (Figure 2a, with zooms in Figure 2b and 2c). Results are presented in relative terms, *i.e.*, as percentages of improvement in total ecosystem services provision with respect to the initial state. In this way, the origin of the axes (0;0) represents the initial states and points on the plot denote percentages of variation in crop production (*x*-axis) or carbon storage (*y*-axis). The color scale represents the energy input.

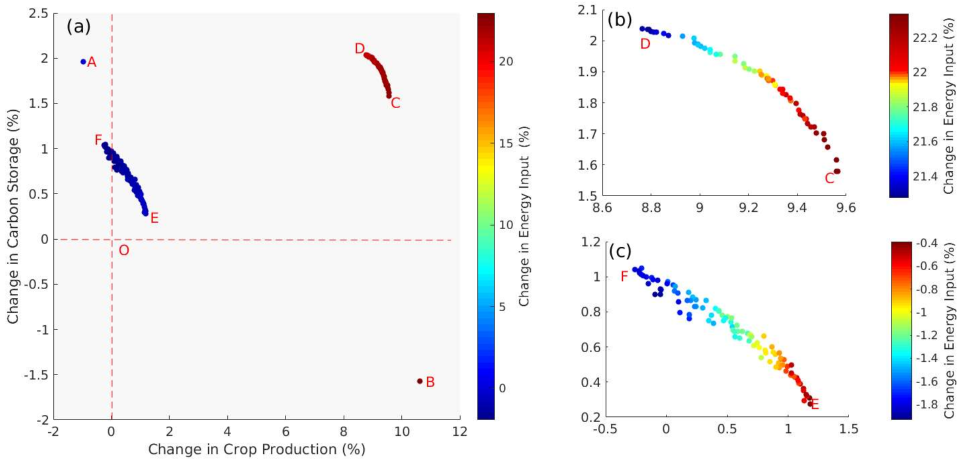

Figure 2 – Pareto frontiers for the four optimization-based scenarios: the mono-objective carbon storage maximisation scenario (point A), the mono-objective crop production maximisation scenario (point B), the bi-objective (carbon storage and crop production joint maximization) optimization (Pareto front limited by points C and D), the tri-objective (joint carbon storage and crop production maximization and energy input minimization). Results are presented in terms of percentage increase with respect to the initial configuration. Panel (a) provides an overview of the results from all the four optimization scenarios; panel (b) represents the zoom of the Pareto front obtained from scenario 3; panel (c) represents the zoom of the Pareto front obtained from scenario 4.

For the mono-dimensional optimization-based scenarios (scenarios 1 and 2) the optimal solution is composed by a point (points A and B, respectively). For the bi-dimensional and tri-dimensional optimization-based scenarios (scenarios 3 and 4), points are distributed along a Pareto frontier. Pareto frontiers composed of all the non-dominated solutions, reflect the existing conflicts in different objectives. Multiple objectives (Bradford and D'Amato 2012) cannot always be maximized or minimized at the same time because trade-offs exist between them, therefore optimal points represent configurations for which it is not possible to improve an objective without worsening another. The shape of the Pareto frontier shows how strict is the conflict among objectives. For scenario 3 the Pareto frontier forms a curved line (delimited by points C and D in Figure 2(a) and zoomed in Figure 2(b)), for scenario 4 the Pareto frontier forms a 3D surface, but it appears as a cloud of points in the two-dimensional representation with a color-gradient scale for the third dimension in Figure 2 (delimited by points E and F in Figure 2(a) and zoomed in Figure 2(c)). In the two Pareto fronts, the energy input increases going to the point maximizing carbon storage (D and F in scenarios 3 and 4, respectively) to the point maximizing crop production (C and E in scenarios 3 and 4, respectively). The shape of the two Pareto fronts show that there is a trade-off between carbon storage and crop production.

Some considerations arise from comparing optimized solutions obtained with different scenarios. The points A and B obtained by the mono-objective scenarios have the highest values at the ecosystem service that they aim at maximizing but the lowest value (lower than the initial configuration) for the other ecosystem service: namely A has a relatively high value of the carbon storage but the lowest crop production and, conversely, B has the highest crop production but the lowest carbon storage. The Pareto front issued from scenario 3 obtains positive improvements in both ecosystem services, however results obtained in crop production and carbon storage are always lower than the values obtained in the respective mono-objective optimizations. The energy input is higher in the results of scenarios 2 and 3 and is lower than in the results of scenarios 1 and 4. Comparing the Pareto fronts obtained with scenarios 3 and 4 makes it visible that the minimization of energy input (included in scenario 4) lowers the optimal value of both ecosystem services.

Land cover changes corresponding to the optimized objectives

Each of the points represented in Figure 2 corresponds to a configuration of land cover and land use. We considered some notable points (indicated with A, B, C, D, E, F in Figure 2) consisting in the results of the mono-objective optimisation scenarios and in the extremes of the Pareto fronts of scenarios 3 and 4, and we analyzed the changes in the land cover fractions observed at the French level for all these points (Figure 3). In point A forest was increased at the expense of annual crops and grassland, while permanent crops and heterogeneous agricultural land are unaffected. In point B forest and grassland were decreased, while arable land and heterogeneous agricultural land were increased. Concerning scenario 3 the land cover configuration in point C and D were quite similar, with an increase in forest and heterogeneous agriculture and a decrease in annual crops, grassland, and (slightly) permanent crops. It is to be noted that energy input was increased all along the C-D pareto frontier (Figure 2(b)). In point C the forest increase and the annual crop decrease were slightly stronger than in point D. Concerning scenario 4, the configurations in points E and F were quite different. In point E (maximizing crop production on the frontier) annual crops and heterogeneous agricultural land were increased, forest was slightly increased, and grassland was decreased. In point F (maximizing carbon storage on the frontier) forest and heterogeneous agricultural land are expanded over grassland, while annual crops and permanent crops remained substantially unchanged.

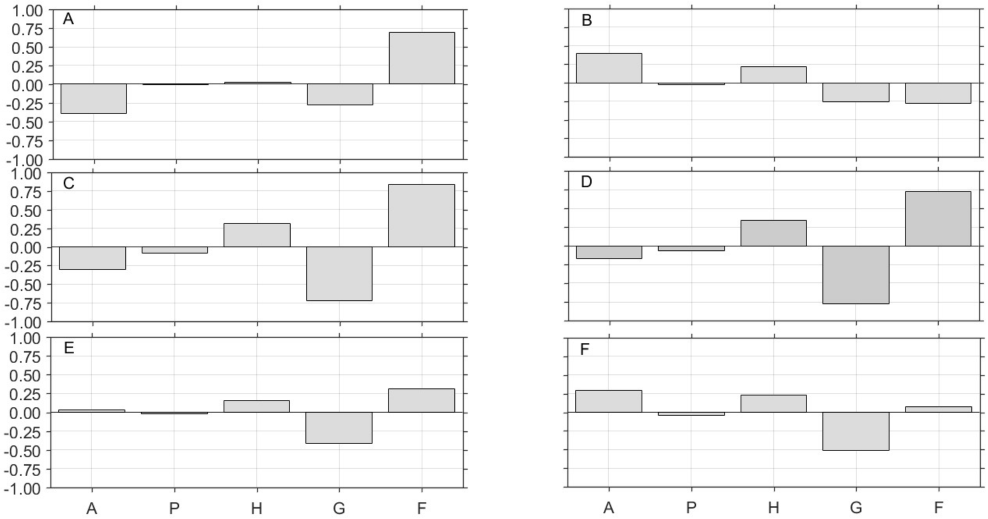

Figure 3 – Percentage of total management area transformed from (negative values) or to (positive values) the different land cover types (A: annual crops; P: permanent crops; H: heterogeneous agricultural land; G: grassland; F: forest). Panels (marked with the letters from A to F corresponds to the points marked on figure 2 with the same letters).

Variations of ecosystem services and energy inputs at the land unit level

We summarized the changes in energy input and ecosystem services provision in the different land units considered. Figure 4 represents the frequency histogram of changes in energy input observed after optimization in the different land units. For observing the changes in ecosystem services provided, for each of the points (A, B, C, D, E, F) marked in Figure 2, we divided the spatial units in four groups: increase in both ecosystem services (group *CP+CS+*), decrease in both ecosystem services (group *CP-CS-*), increase in crop production but decrease in carbon storage (group *CP+CS-*), increase in carbon storage but decrease in crop production (group *CP-CS+*). The percentage of land units in each of those four groups differed according to the scenario and to the point on the Pareto front as shown in Table 3.

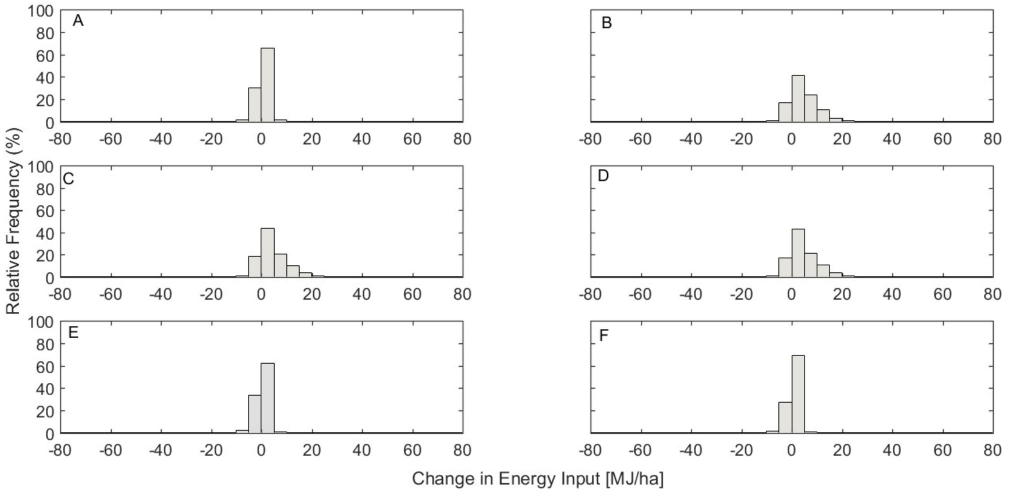

Figure 3 – Relative frequency distribution of the change in energy input per unit of land obtained in the different land units, for the different configurations. Panels (marked with the letters from A to F corresponds to the points marked on figure 2 with the same letters).

In point A the changes in energy input keeps quite low (compared to other scenarios). Although the total energy input increase is relatively low at the French level, some land units see their energy input slightly increased (Figure 4A). The majority of points (40.9%) fall into group *CP-CS+* and some (20.5%) belong to *CP+CS+*, with some land units (14.6%) experiencing decrease in both ecosystem services.

In point B the majority of land units have their energy input increased after the optimization (Figure 4B). A minority of land units have the energy input decreased, but only to a limited extend. The majority of the points (50.6%) belong to the group *CP+CS-* and another relatively high percentage of points (30.7%) belong to the group *CP+CS+*. A low percentage of land units have their crop production decreased.

In points C and D the majority of the land units experience a local increase in energy input (Figures 4C and 4D). A minority of land units experience energy input decrease despite the overall energy input increase at the French level. For these two optimal configurations, the majority of land units are concentrated in the group *CP+CS+*, less points are in *CP+CS-*, less in *CP-CS+* and finally, only a minority of points are in the group *CP-CS-*. The difference between configurations C and D is that in D more land units are classified in groups were crop production increases.

In points E and F the distribution of energy changes is located around zeros without big increases or decreases in energy input (Figures 4E and 4F). In point E the distribution of energy input in the land units is asymmetrical, with more land units having a negative change in energy input. Points E and F have the land units more evenly distributed among the four groups of joint ecosystem services changes. For point E, a higher percentage of land units is concentrated in *CP-CS+*, while in point F, a higher percentage of land units is concentrated in *CP+CS-*.

Table 3 – Percentage of land units belonging to different groups (*CP+CS+*, *CP+CS-*, *CP-CS+*, *CP-CS-*), for the different configurations (letters from A to F corresponding to the points marked in Figure 2). Groups correspond to increase in both crop production and carbon storage (*CP+CS+*), increase in crop production but decrease in carbon storage (*CP+CS-*), increase in carbon storage but decrease in crop production (*CP-CS+*), decrease in both ecosystem services (*CP-CS-*).

Point	*CP+CS+* [%]	*CP+CS-* [%]	*CP-CS+* [%]	*CP-CS-* [%]
A	20.5	24.0	40.9	14.6
B	30.7	50.5	11.8	7.0
C	40.6	34.5	20.6	4.3
D	41.0	37.1	17.8	4.1
E	20.6	28.2	36.6	14.6
F	22.0	33.9	28.9	15.2

Discussion

This paper was aimed at exploring land-cover-land-use-based strategies for addressing the trade-off at the country scale between crop production and carbon storage. We tackled this challenge by formulating statistical models linking land cover, climate, and biophysical variables to the provision of the two ecosystem services considered. We compared optimal solutions coming from four scenarios (Table 1) characterized by an increasing number of objectives in order to explore the trade-off between crop production and carbon storage and the role of intensification in tackling this trade-off. The analysis of land cover and land use changes, both in aggregated manner and in the different land units, made it possible to explain the land use and land cover strategies needed for reaching the optimized solutions.

Comparing scenarios 1 and 2 with scenario 3 highlighted the importance of considering more than one objective in the same optimization problem. Mono-objective scenarios (without any type of constraints on the other objectives) cannot be recommended to policy-makers as they represent myopic policies that do not consider possible negative consequences of other important services. This is in line with recommendation from other scholars (see e.g., Garnett, 2016) and the Millenium Ecosystem Assessment (MEA 2005) where it is encouraged to consider multiple objectives in the process of policy-making. In this study, scenarios 1 and 2 have the demonstrative function of showing that focusing efforts in crop production is detrimental to carbon storage, and *vice versa*. Scenario 2 might be representative of past trajectories in which agricultural expansion and intensification came at the expense of carbon storage (Johnson et al. 2014) as well as of biodiversity (Geiger et al. 2010; Brühl and Zaller 2019) and other ecosystem services (Foley et al. 2005). Scenarios 3 and 4 showed that in the optimized configurations of their Pareto fronts there is a trade-off between crop production and carbon storage. So, the next question is: once the trade-off is rendered visible, how do we deal with it? Comparing scenarios 3 and 4 highlights the role of intensification, while exploring the land cover strategies in the Pareto frontier of scenario 4 highlights the role of different land covers.

The role of grassland in our scenarios

It is important to note that grassland is decreased in all the configurations obtained in all scenarios, especially for configurations E and F. This raises questions about the pertinence of reducing grassland, which is a land cover type contributing to carbon storage and other ecosystem services. Indeed, for the two ecosystem services considered in this study, grassland is not considered an optimal land cover type. It is not as efficient as forest for carbon storage and it is not as productive as cropland for crop production, therefore the optimization algorithm decreases it. In all the configurations, except the B, grassland are converted partially into forests (reforestation/afforestation). This conversion goes in the opposite direction of past land-use change trends but is identified as a climate mitigation and adaptation strategy (Teuling et al. 2019; Lee et al. 2019). Indeed, in the past, increases in the human population and in the demand for animal-sourced food have driven the conversion of forests to semi-natural grassland and/or cropland (Domingues et al. 2018; Feurdean et al. 2018). However, grasslands provide important ecosystem services (Lemaire et al. 2014; Accatino et al. 2019), enhance biodiversity, and reduce feed-food competition (Muscat et al. 2019): they could have been enhanced if other ecosystem services were accounted for in our studies. In addition to this, there are cases in which grasslands simply cannot be converted in other land covers because of pedological and hydrological conditions. This is another reason for putting the constraints on the model decision variables (the variable values in each land units could not exit the range [-20% +20%] of their initial value): in this way, extreme and unrealistic scenarios (that would have maybe strongly reduced grassland) were avoided.

The role of agricultural intensification

If within the Pareto front generated by scenario 3 the trade-off still exists between crop production and carbon storage (Figure 2(b)), the increase of the energy input allows obtaining an increase in both ecosystem services. Along the frontier, the land cover changes are quite similar: intensification makes it possible to obtain a reduction of the surface of annual crops for allowing an expansion of heterogeneous agricultural land and forest, increasing carbon storage. This is in line with land sparing strategies for increasing agricultural production and other natural resources at the same time (Ewers et al. 2009). The expansion of forest occurs in all the configurations, except B. Its expansion, along with the intensification of annual crops, is a land sparing strategy necessary to address the trade-offs among the two ecosystem services. In configuration B forest is reduced because the formulation of the optimization problem does not take into account carbon storage, but only crop production.

The increase in energy makes it possible to promote a land sparing strategy, allowing to reduce land dedicated to agriculture and increasing forest. According to Figure 2(a) energy allows a substantial increase in both ecosystem services. It is however questionable that the increase in yield as a consequence of increased energy input is feasible. First, yields appear to have come to a stagnation point in the last years (Ray et al. 2012; Wiesmeier et al. 2015) and can probably be subject to the uncertainty of future climate change (Challinor et al. 2014). Second, even though yield increase can be achieved by means of the closure of the yield gaps in certain areas (Neumann et al. 2010; van Ittersum et al. 2013), there is ample evidence that agricultural intensification through the use of pesticides, the simplification of landscape and the overuse of mineral fertilizer (Emmerson et al. 2016) is one of the major drivers of drivers of harm to biodiversity and environment (Tanentzap et al. 2015), and depletes the organic matter in the soil (Gervois et al. 2008). The Pareto frontier computed in scenario 3 can therefore be regarded as theoretically attainable, but it shows the role of intensification in pushing the boundaries of the trade-offs between crop production and carbon storage. Pathways of sustainable intensification, through the use of precise fertilization techniques (Godfray 2015) and other practices, can improve yields without damage to the environment (Tscharntke et al. 2005; Garratt et al. 2018). They can push the configurations beyond the Pareto front of scenario 4, improving the provision of both ecosystem services, if not to the Pareto front of scenario 3, to some points in between. However, debate exists around the possibility of pushing intensification while reducing (or not increasing) the impact of agriculture on the environment (Godfray 2015) and its implementation on a large scale is questionable (Crist et al. 2017).

The role of expansion of agricultural land and heterogeneous agriculture

When energy input is minimized, changing the land cover fractions becomes primary to tackle the trade-off between crop production and carbon storage. The improvement of the two ecosystem services in scenario 4 is limited if compared to scenario 3 and, in some cases, crop production is even lowered (with respect to the initial state) in order to increase carbon storage. Both annual crops and forest are increased in scenario 4, to different extents according to the ecosystem services enhanced along the Pareto frontier.

All the scenarios show the important contribution of heterogeneous agricultural land in addressing the trade-off between crop production and carbon storage. Within scenario 3, heterogeneous agricultural land is still increased, but with also an increase of energy input: in this scenario heterogeneous agricultural land can be increased, but in a frame of land sparing, i.e., the annual crops are intensified. Within scenario 4, heterogeneous agricultural land is key because energy input is minimized. It becomes very important therefore to promote this land use which is able to provide both ecosystem services at the same time with less energy input need than monocultures (Alluvione et al. 2011) and less dependency on fossil fuels (Melézieux 2012). Only permanent crops have also this potential, but due to their low percentage in France (compared to other land cover types), they do not have a prominent role in the scenarios. The message behind this is that land covers promoting both crop production and carbon storage are fundamental for tackling the trade-off. The idea is to bring nature into agriculture so to promote carbon storage within agriculture. This can be achieved with practices of conservation, organic, and integrated agriculture (Autret et al. 2016), based on no-tillage (Triplett Jr and Dick 2008), cover crops (Schipanski et al., 2014), re-incorporation or selective removal of crop residues (Stella et al. 2019)and other practices (see Singh et al.,

2018) . Agroforestry is also a promising way to promote the two functions at the same time (Jose 2009).

The expansion of annual crops showed above all in configuration F could be framed in the concept of “selective expansion” proposed by Johnson et al., (2014), for which the expansion of crops should occur in selected lands for minimizing soil carbon losses due to land cover conversion. In this configuration, according to Figure 2, the percentage loss in crop production can be considered small in comparison to the percentage increase in carbon storage that can be gained. One can argue that it is not strictly necessary to increase crop production in Europe (even though this need should be put in perspective with climate change scenarios), but simply to increase carbon storage without decreasing crop production (win-no-loss solution). The Pareto frontier of scenario 4 showed that this is possible, like Teillard et al. (2017)showed that this is possible between crop production and biodiversity at the French scale.

The role of spatial distribution of land use change and consideration on land sparing and land sharing

Following Fischer et al. (2014), the debate about land sparing and land sharing can be addressed at different spatial scales. Accatino et al. (2019) made considerations comparing the French scale with lower-scale land units and showed that even though a land sharing strategy can be visible at the country level, a land sparing strategy can be visible in smaller spatial units. In this study, configurations B, C, and D are characterized by an increase in energy input at the country level and, in particular, C and D tackles the trade-off between crop production and carbon storage at the country level with a land sparing strategy (increase in energy input and decrease of annual crops). For configuration B almost half of the land units are characterized by an increase of crop production over carbon storage and an increase in energy input. For configurations C and D many land units are also locally characterized by land sparing, with a local intensification and local increase in both ecosystem services. However, a minority of land units are characterized by a local increase in carbon storage and a decrease in energy input.

The analysis of points E and F, which are characterized by a strategy at the French level close to the land sharing strategy (low energy input, expansion of annual crops, forest, and agricultural land) show that in some land units the energy input is increased. Similarly, some land units are locally characterized by an increase in crop production at the detriment of carbon storage. This is in line with the re-allocation scenario shown by Teillard et al. (2017)in which it was possible to conciliate biodiversity and agricultural production. However, the re-allocation can cause inequalities with different winners and losers distributed in space and parts of the country in which increases in agricultural land and agricultural inputs might cause local detriment to natural resources. This would not be socially acceptable (Rutz et al. 2014) and should be carefully addressed in policy-making.

General remarks

The modelling approach has some limitations: it is limited to data available at the large scale and includes only a part of the land cover and land use variable possible; in addition to this, some data was aggregated (for example energy input included a number of elements such as synthetic fertilization and machinery). However, the approach allows exploring strategies of land use allocation and trade-offs at the large scale among ecosystem services. Other ecosystem services can be included in the modelling, for example, Accatino et al. (2019) considered four ecosystem services at the same scale. From the lessons learnt with this study, we can affirm that adding new objective will render it even more difficult to find solutions that improve all the objective desired, but the comparison of scenarios done with different number of objectives included, like in this study, will make it possible to detect the role of each objective in the complex trade-off. We can extend another finding from this study: land covers providing multiple ecosystem services are to be preferred, for example forest are acknowledged and demonstrated to provide a wide array of ecosystem services (Maes et al. 2012) and some forms of agriculture and agroforestry make agriculture more multi-functional.

Our study provides perspectives at the large scale, but if this is a panoramic view for policy-making, the implementation of the solutions comes from applying multiple local land use changes. This requires evaluating issues related to land use conflicts (Zou et al. 2019) which need to take into account socio-economic dynamics (Tudor et al. 2014) and are influenced by policies (Milczarek-Andrzejewska et al. 2018).

Conclusion

This study tackled the trade-off between crop production and carbon storage at the large scale via a set of optimization scenarios. Comparing different optimization scenarios with different number of objectives makes it possible to understand the role of different variables and different number of objectives considered. Specifically, adding more objectives decrease the possibility to increase them, and the objective of energy input minimization decrease the extent at which both carbon storage and crop production can be jointly increased.

On the one hand, our modelling results highlighted the need of promoting carbon storage within agriculture via the enhancement of heterogeneous agriculture as well as with practices of no-tillage, agroforestry, and other forms of organic, integrated, conservation agriculture. Some previous studies highlighted the importance of increasing soil carbon storage out of the currently used agricultural lands, which have the highest potential of sequestrating new carbon (Lal et al. 2015). On the other hand, the study also highlighted the need of managing the conflict between agricultural land with grassland and forest which store higher amount of carbon than arable land. The model showed that the land sparing approach can save some land: intensification of agricultural land might save some land for new afforestation or restoration of ecosystems; however, the energy input in agriculture should be sustainable. Future modelling approaches might consider different degrees of intensification, according to how sustainable it can be considered and might parametrize the influence of agricultural practices, in this way trade-offs among crop production and carbon storage can be studies more in detail.

References

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

Alluvione F, Moretti B, Sacco D, et al (2011). EUE (Energy Use Efficiency) of Cropping Systems for a Sustainable Agriculture. Energy 36 (7): 4468–81. https://doi.org/10.1016/j.energy.2011.03.075.

Anand R, Aggarwal D, Kumar V (2017) A comparative analysis of optimization solvers. J Stat Manag Syst 20:623–635. https://doi.org/10.1080/09720510.2017.1395182

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

Bradford JB, D'Amato AW (2012) Recognizing trade-offs in multi-objective land management. Front Ecol Environ 10:210–216. https://doi.org/10.1890/110031

Brühl CA, Zaller JG (2019) Biodiversity decline as a consequence of an inadequate environmental risk assessment of pesticides. Front Environ Sci 7:177. https://doi.org/10.3389/fenvs.2019.00177

Butchart SH, Walpole M, Collen B, et al (2010) Global biodiversity: indicators of recent declines. Science 328:1164–1168. https://doi.org/10.1126/science.1187512

Castelletti A, Pianosi F, Soncini-Sessa R, Antenucci J (2010) A multiobjective response surface approach for improved water quality planning in lakes and reservoirs. Water Resour Res 46:6. https://doi.org/10.1029/2009WR008389

Chabbi A, Lehmann J, Ciais P, et al (2017) Aligning agriculture and climate policy. Nat Clim Change 7:307–309. https://doi.org/10.1038/nclimate3286

Challinor AJ, Watson J, Lobell DB, et al (2014) A meta-analysis of crop yield under climate change and adaptation. Nat Clim Change 4:287–291. https://doi.org/10.1038/nclimate2153

Commission of the European Union. Joint Research Centre. (2015) Agricultural biomass as provisioning ecosystem service: quantification of energy flows. Publications Office, LU

Cotrufo MF, Ranalli MG, Haddix ML, et al (2019) Soil carbon storage informed by particulate and mineral-associated organic matter. Nat Geosci 12:989–994. https://doi.org/10.1038/s41561-019-0484-6

Crist E, Mora C, Engelman R (2017) The interaction of human population, food production, and biodiversity protection. Science 356:260–264. https://doi.org/10.1126/science.aal2011

Daily GC (1997) Nature's services. Island Press, Washington, DC

Deguines N, Jono C, Baude M, et al (2014) Large-scale trade-off between agricultural intensification and crop pollination services. Front Ecol Environ 12:212–217. https://doi.org/10.1890/130054

Domingues JP, Ryschawy J, Bonaudo T, et al (2018) Unravelling the physical, technological and economic factors driving the intensification trajectories of livestock systems. Animal 12:1652–1661. https://doi.org/10.1017/S1751731117003123

Ellert B, Janzen H, McConkey B, Lal R (2001) Measuring and comparing soil carbon storage. Assess Methods Soil Carbon 131–146. https://doi.org/10.1111/gcb.14815

Emmerson M, Morales M, Oñate J, et al (2016) How agricultural intensification affects biodiversity and ecosystem services. In: Advances in ecological research. Elsevier, pp 43–97. https://doi.org/10.1016/bs.aecr.2016.08.005

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

European commission, Joint research centre, Institute for environment and sustainability (Ispra I, et al (2011) A European assessment of the provision of ecosystem services Towards an atlas of ecosystem services. Publications Office of the European Union, Luxembourg

European Environmental Agency (EEA), 2013. CORINE Land Cover (CLC), 2006, Version 17. European Environmental Agency (EEA), Kopenhagen K., Denmark. https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster-4

Ewers RM, Scharlemann JP, Balmford A, Green RE (2009) Do increases in agricultural yield spare land for nature? Glob Change Biol 15:1716–1726. https://doi.org/10.1111/j.1365-2486.2009.01849.x

Feurdean A, Ruprecht E, Molnár Z, et al (2018) Biodiversity-rich European grasslands: Ancient, forgotten ecosystems. Biol Conserv 228:224–232. https://doi.org/10.1016/j.biocon.2018.09.022

Fischer J, Abson DJ, Butsic V, et al (2014) Land Sparing Versus Land Sharing: Moving Forward: Land sparing versus land sharing. Conserv Lett 7:149–157. https://doi.org/10.1111/conl.12084

Foley JA, DeFries R, Asner GP, et al (2005) Global consequences of land use. science 309:570–574. https://doi.org/10.1126/science.1111772

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

Gao P, Wang H, Cushman SA, et al (2020) Sustainable land-use optimization using NSGA-II: theoretical and experimental comparisons of improved algorithms. Landsc Ecol 1–16. https://doi.org/10.1007/s10980-020-01051-3

Garnett T (2016) Plating up solutions. Science 353:1202–1204. https://doi.org/10.1126/science.aah4765

Garratt MP, Bommarco R, Kleijn D. et al (2018) Enhancing soil organic matter as a route to ecological intensification of European arable systems. Ecosystems 21:1404-1415. https://doi.org/10.1007/s10021-018-0228-2.

Geiger F, Bengtsson J, Berendse F, et al (2010) Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl Ecol 11:97–105. https://doi.org/10.1016/j.baae.2009.12.001

Gervois S, Ciais P, de Noblet-Ducoudré N et al (2008) Carbon and water balance of European croplands throughout the 20th century. Global Biogeochem Cycles 22 GB2022. https://doi.org/10.1029/2007GB003018.

Godfray HCJ (2015) The debate over sustainable intensification. Food Secur 7:199–208. https://doi.org/10.1007/s12571-015-0424-2. https://doi.org/10.1007/s12571-015-0424-2

Godfray HCJ, Beddington JR, Crute IR, et al (2010) Food security: the challenge of feeding 9 billion people. science 327:812–818. https://doi.org/10.1126/science.1185383

Grammatikopoulou I, Sylla M, Zoumides C (2020) Economic evaluation of green water in cereal crop production: A production function approach. Water Resour Econ 29:100148. https://doi.org/10.1016/j.wre.2019.100148

Green RE, Cornell SJ, Scharlemann JP, Balmford A (2005) Farming and the fate of wild nature. science 307:550–555. https://doi.org/10.1126/science.1106049

Groot JC, Yalew SG, Rossing WA (2018) Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach. Landsc Urban Plan 172:29–36. https://doi.org/10.1016/j.landurbplan.2017.12.008

Hadka D (2015) Moea framework-a free and open source java framework for multiobjective optimization. version 2.11. URL Httpwww Moeaframework Org

Hiederer R, European Commission, Joint Research Centre, Institute for Environment and Sustainability (2012) EFSA spatial data version 1.1: data properties and processing. Publications Office, Luxembourg

IPCC (2018) Reports — IPCC. https://www.ipcc.ch/reports/. Accessed 17 Dec 2020

Johnson JA, Runge CF, Senauer B, et al (2014) Global agriculture and carbon trade-offs. Proc Natl Acad Sci U S A 111:12342–12347. https://doi.org/10.1073/pnas.1412835111

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76:1–10. https://doi.org/10.1007/s10457-009-9229-7

Kell DB (2012) Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: Why and how. Philos Trans R Soc B Biol Sci 367:1589–1597. https://doi.org/10.1098/rstb.2011.0244

Kon Kam King J, Granjou C, Fournil J, Cecillon L (2018) Soil sciences and the French 4 per 1000 Initiative—The promises of underground carbon. Energy Res Soc Sci 45:144–152. https://doi.org/10.1016/j.erss.2018.06.024

Kremen C, Ostfeld RS (2005) A call to ecologists: measuring, analyzing, and managing ecosystem services. Front Ecol Environ 3:540–548. https://doi.org/10.1890/1540-9295(2005)003[0540:ACTEMA]2.0.CO;2

Lal R, Negassa W, Lorenz K (2015) Carbon sequestration in soil. Curr Opin Environ Sustain 15:79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Lee H, Brown C, Seo B, et al (2019) Implementing land-based mitigation to achieve the Paris Agreement in Europe requires food system transformation. Environ Res Lett 14:104009. https://doi.org/10.1088/1748-9326/ab3744

Lemaire G, Franzluebbers A, de Faccio Carvalho PC, Dedieu B (2014) Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric Ecosyst Environ 190:4–8. https://doi.org/10.1016/j.agee.2013.08.009

Li SC, Zhang CY, Liu JL, et al (2013) The tradeoffs and synergies of ecosystem services: Research progress, development trend, and themes of geography. Geogr Res 32:1379–1390. http://www.dlyj.ac.cn/EN/Y2013/V32/I8/1379

Maes J, Fabrega N, Zulian G, et al (2015) Mapping and assessment of ecosystems and their services: trends in ecosystems and ecosystem services in the European Union between 2000 and 2010. Publications Office, Luxembourg

Maes J, Paracchini ML, Zulian G, et al (2012) Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. Biol Conserv 155:1–12. https://doi.org/10.1016/j.biocon.2012.06.016

Malézieux E (2012) Designing Cropping Systems from Nature. Agron Sustain Dev 32(1): 15–29. https://doi.org/10.1007/s13593-011-0027-z.

Metzger Mj, Rounsevell M, Acosta-Michlik L, et al (2006) The vulnerability of ecosystem services to land use change. Agric Ecosyst Environ 114:69–85. https://doi.org/10.1016/j.agee.2005.11.025

Milczarek-Andrzejewska D, Zawalińska K, Czarnecki A (2018) Land-use conflicts and the Common Agricultural Policy: Evidence from Poland. Land Use Policy 73:423–433. https://doi.org/10.1016/j.landusepol.2018.02.016

Millenium Ecosystem Assessment (MEA) (2005). Ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington, DC, USA.

Muscat A, de Olde E, de Boer IJ, Ripoll-Bosch R (2019) The battle for biomass: A systematic review of food-feed-fuel competition. Glob Food Secur 100330.

https://doi.org/10.1016/j.gfs.2019.100330

Neumann K, Verburg PH, Stehfest E, Müller C (2010) The Yield Gap of Global Grain Production: A Spatial Analysis. Agr Sys 103: 316–26. https://doi.org/10.1016/j.agsy.2010.02.004.

Pellegrini P, Fernández RJ (2018) Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. Proc Natl Acad Sci 115:2335–2340. https://doi.org/10.1073/pnas.1717072115

Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333:1289–1291. https://doi.org/10.1126/science.1208742

Ray DK, Ramankutty N, Mueller ND, et al (2012) Recent patterns of crop yield growth and stagnation. Nat Commun 3:1–7. https://doi.org/10.1038/ncomms2296

Rumpel C, Amiraslani F, Chenu C, et al (2020) The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49:350–360. https://doi.org/10.1007/s13280-019-01165-2

Rutz C, Dwyer J, Schramek J (2014) More new wine in the same old bottles? The evolving nature of the CAP reform debate in europe, and prospects for the future. Sociol Rural 54:266–284. https://doi.org/10.1111/soru.12033

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

Schroder SAK, Tóth SF, Deal RL, Ettl GJ (2016) Multi-objective optimization to evaluate tradeoffs among forest ecosystem services following fire hazard reduction in the Deschutes National Forest, USA. Ecosyst Serv 22:328–347. https://doi.org/10.1016/j.ecoser.2016.08.006

Seppelt R, Lautenbach S, Volk M (2013) Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales. Curr Opin Environ Sustain 5:458–463. https://doi.org/10.1016/j.cosust.2013.05.002.

Setälä H, Bardgett R, Birkhofer K, et al (2014) Urban and agricultural soils: conflicts and trade-offs in the optimization of ecosystem services. Urban Ecosyst 17:239–253. https://doi.org/10.1007/s11252-013-0311-6.

Shaygan M, Alimohammadi A, Mansourian A, et al (2013) Spatial multi-objective optimization approach for land use allocation using NSGA-II. IEEE J Sel Top Appl Earth Obs Remote Sens 7:906–916. https://doi.org/10.1109/JSTARS.2013.2280697

Shin-ichiro SM, Kohzu A, Kadoya T, et al (2019) Role of wetlands in mitigating the trade-off between crop production and water quality in agricultural landscapes. Ecosphere 10: e02918. https://doi.org/10.1002/ecs2.2918

Smith P (2016) Soil carbon sequestration and biochar as negative emission technologies. Glob Change Biol 22:1315–1324. https://doi.org/10.1111/gcb.13178

Song M, Chen D (2018) An improved knowledge-informed NSGA-II for multi-objective land allocation (MOLA). Geo-Spat Inf Sci 21:273–287. https://doi.org/10.1080/10095020.2018.1489576

Soussana JF, Lutfalla S, Ehrhardt F, et al (2019) Matching policy and science: Rationale for the ‘4 per 1000 - soils for food security and climate’ initiative. Soil Tillage Res 188:3–15. https://doi.org/10.1016/j.still.2017.12.002

Stella T, Mouratiadou I, Gaiser T, et al (2019) Estimating the contribution of crop residues to soil organic carbon conservation. Environ Res Lett 14:. https://doi.org/10.1088/1748-9326/ab395c

Tanentzap AJ, Lamb A, Walker S, Farmer A (2015) Resolving conflicts between agriculture and the natural environment. PLoS Biol 13:e1002242. https://doi.org/10.1371/journal.pbio.1002242

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

Teuling AJ, de Badts EAG, Jansen FA, et al (2019) Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe. Hydrol Earth Syst Sci 23:3631–3652. https://doi.org/10.5194/hess-23-3631-2019

Tóth SF, Ettl GJ, Könnyű N, et al (2013) ECOSEL: Multi-objective optimization to sell forest ecosystem services. For Policy Econ 35:73–82. https://doi.org/10.1016/j.forpol.2013.06.011

Triplett Jr GB, Dick WA (2008) No-tillage crop production: A revolution in agriculture! Agron J 100:S-153. https://doi.org/10.2134/agronj2007.0005c

Tscharntke T, Klein AM, Kruess A, et al (2005) Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. Ecol Lett 8:857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Tudor CA, Iojă IC, Pătru-Stupariu I, et al (2014) How successful is the resolution of land-use conflicts? A comparison of cases from Switzerland and Romania. Appl Geogr 47:125–136. https://doi.org/10.1016/j.apgeog.2013.12.008

van Ittersum MK, Cassman KG, Grassini P, et al. (2013) Yield gap analysis with local to global relevance-a review. Field Crop Res 143:4-17. https://doi.org/10.1016/j.fcr.2012.09.009.

Virto I, Barré P, Burlot A, Chenu C (2012) Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry 108:17–26. https://doi.org/10.1007/s10533-011-9600-4

Wiesmeier M, Hübner R, Kögel-Knabner I (2015) Stagnating crop yields: An overlooked risk for the carbon balance of agricultural soils? Sci Total Environ 536:1045–1051. https://doi.org/10.1016/j.scitotenv.2015.07.064

Zhang Q, Dong W, Wen C, Li T (2020) Study on factors affecting corn yield based on the Cobb-Douglas production function. Agric Water Manag 228:105869

Zou L, Liu Y, Wang J, et al (2019) Land use conflict identification and sustainable development scenario simulation on China's southeast coast. J Clean Prod 238:. https://doi.org/10.1016/j.jclepro.2019.117899

Supplementary material

Table 1 – Correspondence between the land cover class used in the model and the Corine Land Cover classification.

Abbreviation	Land cover	Composition
A	Arable crop land	2.1.1 Non-irrigated arable land 2.1.2 Permanently irrigated land 2.1.3 Rice fields
P	Permanent crop land	2.2.1 Vineyards 2.2.2 Fruit trees and berry plantations 2.2.3 Olive groves
H	Heterogeneous agricultural areas	2.4.1 Annual crops associated with permanent crops 2.4.2 Complex cultivation patterns 2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation 2.4.4 Agro-forestry areas
G	Grassland	3.2.1 Natural grasslands 3.2.2 Moors and heathland 3.2.3 Sclerophyllous vegetation

		3.2.4 Transitional woodland-shrub
F	Forests	3.1.1 Broad-leaved forest 3.1.2 Coniferous forest 3.1.3 Mixed forest