frontiers | Frontiers in Environmental Science

Productive versus environmental objectives of agricultural policies dealing with climate change: a French case study

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The study aims at reconciling contrasting productive and environmental goals of agricultural policies at a given budget in the context of climate change. Based on a quantitative bioeconomic model integrating interdependencies between agricultural systems and agroecosystems, we compare the impacts of 4 contrasted public policy scenarios based either on productive (food or energy) or environmental goals (pollution reduction or ecosystem state) on a set of 18 bioeconomic indicators. We run the policy scenarios under two contrasted climate change scenarios to investigate their robustness. We confirm that it is possible to achieve productive and environmental goals with the on-going budget of European agricultural policy. Synergies between productive and environmental performances exist even if they are not trivial nor systematic. More precisely, an agricultural public policy which focuses on energy production might offer a good compromise regarding the different facets of agricultural landscapes. The Pollution scenario constitutes a credible environmentally oriented alternative even if it remains slightly less competitive regarding both ecological and economic sides than an energy-oriented policy. Eventually, our analysis shows that our conclusions are robust to climate change, suggesting that adequate agricultural public policies might attenuate climate change effects when considering intermediary climate change scenarios.

1 Introduction

The degradation of biodiversity constitutes one of the critical global issues for humanity (Convention on Biological Diversity and United Nations Environment Programme, 2014; Loh, 2014; Díaz et al., 2019). Regarding terrestrial ecosystems, land use changes including urbanization, agricultural abandonment or intensification of agricultural landscapes have been identified as the main causes of this erosion in Europe and in France over the last decades (Chamberlain et al., 2000; Donald et al., 2001; Gregory et al., 2017). These changes in land uses lead to a decrease and a

degradation of the habitats available for biodiversity, along with their fragmentation (Robinson et al., 1995). Beyond this ecological concern, such an erosion of ecosystems strongly impacts human well-being by interfering with the provision of ecosystem services (MEA, 2005; Costanza et al., 2017; Díaz et al., 2019). Due to these unexpected economic impacts, a debate has emerged about the economic rationale driving changes in land uses.

The European Common Agricultural Policy (CAP) (see Table 1 for the complete list of acronyms) constitutes an interesting case-study for this debate. For 30 years, it has articulated a first set of measures (the "first pillar") historically dedicated to production with a second set (the "second pillar") dedicated to rural and environmental development (Swinton et al., 2007). Despite recent developments which tend to include environmental conditions within the first pillar, this dual structure remains at the core of the discussions of CAP (Pe'er et al., 2014; Mouysset, 2014). The concept of ecosystem service brings a new perspective on this duality. Indeed, on one side, the historical economic rationale of agricultural land use changes is related to the provision of ecosystem services, namely food and energy provision (Lowe et al., 2002). On the other side, the negative environmental impacts of land use changes over the last 50 years (such as the impacts on pollinators or pest controls (Bianchi et al., 2006; Ricketts et al., 2008), on carbon and nitrogen cycles (Batlle-Aguilar et al., 2011) and on emblematic species (Tucker and FHeath., 1994; Benton et al., 2002)) involve regulating, supporting and cultural ecosystem services. In this perspective, the challenge of agricultural public policies aiming at articulating productive and environmental objectives consists in providing the whole bundle of ecosystem services (Strijker, 2005; Stoate et al., 2009). To help decision-makers, a literature on ecosystem services has grown significantly in recent years (Bateman et al., 2013; Mouysset et al., 2016; Elalamy et al., 2019; Mouysset et al., 2019). However the identification of a socially acceptable and sustainable trade-off between ecosystem services is still in debate. In such a context, the design of a socially acceptable and sustainable European agricultural public policy remains an open question.

This question takes place in an additional challenging context regarding climate change (Masson-Delmotte et al., 2021). Indeed, the Special Report on Climate Change and Land warns about terrestrial ecosystems and biodiversity vulnerability to climate change and extreme weather conditions (Newbold, 2018; Shukla et al., 2019; Taheri et al., 2021). Climate change directly affects ecosystems. More precisely, the growing pace of isotherms' displacement leads to a spatial mismatch between bio-climatic niches and available habitat (Devictor et al., 2008) which increases the climatic debt (Kapitza et al., 2021) and the extinction risk (Pearson et al., 2014; Singer et al., 2016). These mismatches emerge from changes in phenology (Gaüzère et al., 2016), habitat quality (Holyoak and Heath, 2016), inter-species interactions

(LeBrun et al., 2016; Dalsgaard, 2020) and food ressources (Mantyka-Pringle et al., 2019). Moreover, extreme events during the reproduction period hinder the reproductive success and the survival rate, leading to a population decline (Bellard et al., 2012; Gaüzère et al., 2016).

Beside these direct impacts on ecosystems, climate change creates additional pressures on lands and land use change. More specifically, climate change affects agricultural yields generating an increase or a decrease in land uses depending on the type of crops, the location, the soil quality and the climate conditions (Souty et al., 2013; European Commission Research Centre, Joint et al., 2020). By affecting land use distributions, climate change impacts habitat availability, thus exacerbating existing risks on biodiversity and ecosystem health (Martin et al., 2013; Mantyka-Pringle et al., 2015). In spite of numerous scientific studies, these amplifying mechanisms are still poorly understood (Oliver and Morecroft, 2014). Many interactive effects remain unexpected, generating some "ecological surprises" (Pörtner et al., 2021). Feedback loops, synergistic mechanisms and threshold effects make estimations of the impact of climate change on ecosystems and human well-being imprecise (Elmhagen et al., 2015; Peters et al., 2019).

Despite this complexity, the scientific community agrees that the combined effects of climate change and land-use change are mutually reinforcing (de Chazal and Rounsevell, 2009; Ay et al., 2014; Oliver and Morecroft, 2014). While climate projections for the next few years are already determined due to climate inertia, longer term outcomes given future climate action are less certain. Hence, decision-makers have the opportunity to consider different longer term climate scenarios in designing their agricultural policies (Dunford et al., 2015; Mouchet et al., 2017). It is precisely to reduce or counteract the negative impacts of land use on biodiversity in the context of climate change that Climate and Agri-Environmental Schemes (CAES) have been developed in Europe since 2014. Indeed the IPCC report indicates that maximizing synergies between sustainable and integrated land management on the one hand, and climate change adaptation and mitigation measures on the other, can generate co-benefits for biodiversity, ecosystem services and human well-being (Shukla et al., 2019). In this context, there is an urgent need to explicitly consider different climate change trends when designing agricultural policies.

Interdisciplinary studies based on bioeconomic models integrating complex interdependencies between ecosystems and human society (Jean and Mouysset, 2022) offer the holistic view required to investigate the trade-offs between ecosystem services provided by agricultural landscapes in a context of climate change (Bateman et al., 2013; Oliver and Morecroft, 2014; Mouysset et al., 2019; Rosa et al., 2020). Following this perspective, we developed a quantitative bioeconomic model based on Mouysset et al. (2019), in order to optimize the characterization of productive and environmental objectives of agricultural policies, using

synergies between ecosystem services. The bioeconomic model is based on the coupling of an ecological model of bird dynamics with a microeconomic model of land use management. Particular attention is paid to the modeling of ecological dynamics, in agreement with Elmhagen et al. (2015) and Newbold, (2018) who reaffirm the need for mechanistic ecological models. In this study, we investigate 4 contrasted public policy scenarios regarding different productive and environmental goals: food provision, energy provision, pollution decrease and ecosystem preservation. We assess the impact of such policy scenarios on a set of 18 bioeconomic indicators. We evaluate the robustness of these performances in the face of climate change by exploring two contrasted climate change scenarios.

Our study confirms that it is possible to achieve productive and environmental goals with the current European agricultural policy budget. Our study illustrates that synergies between productive and environmental performances do exist even if they are not trivial nor systematic. More precisely, an agricultural public policy which focuses on energy production might offer a compromise regarding the different functions of agricultural landscapes, including productive and environmental ones. The pollution decrease scenario constitutes a credible environment-oriented alternative even if it remains slightly less competitive regarding both ecological and economic sides compared to an energy-oriented policy. Eventually, our analysis shows that our conclusions are robust to different climate change scenarios, suggesting that adequate agricultural public policies might attenuate climate change effects when considering intermediary climate change scenarios.

2 Materials and methods

2.1 The bioeconomic model

2.1.1 The bioeconomic framework

The bioeconomic model presented in Figure 1 is adapted from the bioeconomic framework developed in Mouysset et al. (2019). Similarly, it articulates a national decision maker, who implements national public policies in a context of climate change, with a range of regional planners who optimize their land use distribution, which in turn affect regional birds communities. However, it differs from the initial framework in 3 respects. First, this new model details the agronomic strategies of regional planners: in addition to considering land use distribution, they are now able to choose the level of inputs dedicated to each crop. Second, it integrates feedback impacts from ecosystems on regional planners through ecosystem services affecting the marginal yields of pollination-sensitive crops. In other words, we did not consider biodiversity provisioning per se (as a cultural ecosystem service) but biodiversity provisioning for food production (as a regulating ecosystem service). Third,
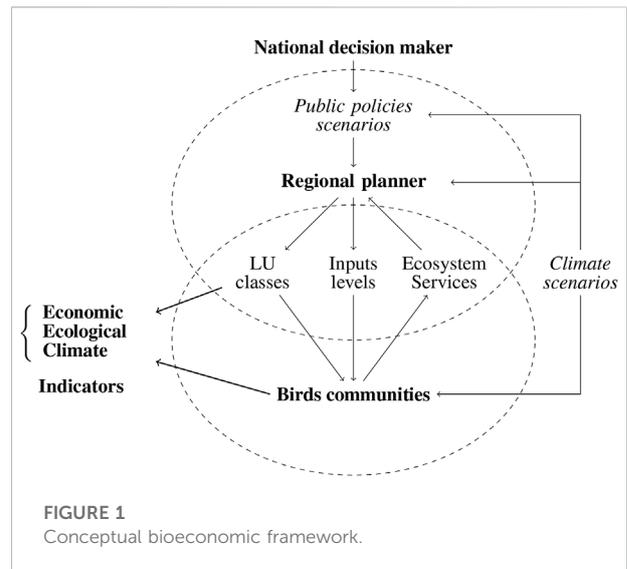

FIGURE 1
Conceptual bioeconomic framework.

climate change is not solely taken into consideration in the ecological model but also by the national policy-maker, who investigates different climate scenarios.

2.1.2 The economic model

We consider regional landscapes, each managed by a representative landowner driven by economic rationality. In each period, the regional economic agent determines the surfaces $S_{r,l}$ dedicated to each land use l and the chemical inputs, namely pesticides $P_{r,l}$ and fertilizers $F_{r,l}$, in order to maximize her regional profit Π_r under technical-economic constraints such as in Kapitza et al. (2021). The optimization program in a region r is detailed below.

First, the objective function of the regional land planner is defined as follows:

$$
\max_{S_{r,l}(t), P_{r,l}(t), F_{r,l}(t)} \Pi_r(t) = \sum_l S_{r,l}(t)
$$
$$
\times \left[\pi_{r,l}^* \left(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t) \right) + \delta_l \right]
\tag{1}
$$

where $\pi_{r,l}^* \left(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t) \right)$ stands for the marginal rent of land use l in region r with respective pesticides and fertilizers inputs $P_{r,l}(t)$ and $F_{r,l}(t)$, an ecosystem providing a certain level of ecosystem services $E_r(t)$ under climate conditions $C_r(t)$, while δ_l stands for the public policy incentive dedicated to land use l. We come back to δ_l in Section 3.1, focusing on public policy scenarios.

The marginal rent $\pi_{r,l}^* \left(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t) \right)$ of land use l in region r comes from maximizing the following function with respect to the use of inputs (pesticides and fertilizers):

$$
\pi_{r,l}^* \left(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t) \right) = \max_{P_{r,l}(t), F_{r,l}(t)} p_l \rho \left(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t) \right)
$$
$$
- c_P P_{r,l}(t) - c_F F_{r,l}(t)
\tag{2}
$$

where p_l, c_P and c_F are respectively the national sale prices for production of land use l, and the costs of pesticides and fertilizers. For the sake of simplicity, these 3 parameters are considered constant over time in this study. The expression $\rho(F_{r,l}(t), P_{r,l}(t), E_r(t), C_r(t))$ stands for the agronomic yield function.

Following Souty et al. (2013), the agronomic yields $\rho(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t))$ are modeled as an increasing function of pesticides and fertilizers. Diminishing yields are approximated by a bounded linear function: the agronomic yields cannot exceed a threshold value for given bioclimatic conditions $\rho_{r,l}^{sup}(E_r(t), C_r(t))$, nor fall below a certain threshold $\rho_{r,l}^{0}(E_r(t), C_r(t))$ (maintenance of minimal yields even without external input). More precisely, agronomic yields are defined as:

$$\rho(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t)) = \rho_{r,l}^{0}(E_r(t), C_r(t)) + \alpha_{P,l} P_{r,l}(t) + \alpha_{F,l} F_{r,l}(t) \quad (3)$$

with respect to:

$$\rho_{r,l}^{0}(E_r(t), C_r(t)) \le \rho(P_{r,l}(t), F_{r,l}(t), E_r(t), C_r(t)) \le \rho_{r,l}^{sup}(E_r(t), C_r(t)) \quad (4)$$

Parameters $\alpha_{P,l}$ and $\alpha_{F,l}$ stand for the responses of crops on land use l to pesticides and fertilizers respectively. For the sake of simplicity, we assume that they are constant. Eventually, the range of possible agronomic yields for land use l in region r $[\rho_{r,l}^{0}(E_r(t), C_r(t)); \rho_{r,l}^{sup}(E_r(t), C_r(t))]$ depends on ecosystem services $E_r(t)$ provided by the ecosystem of region r at time t and the climate conditions $C_r(t)$ as follows:

$$\rho_{r,l}^{0}(E_r(t), C_r(t)) = \kappa_{r,l}^{0}\left(1 + \kappa_{r,l}^{0,C}(t) + \kappa_{r,l}^{0,E} E_r(t)^{\nu}\right) \quad (5)$$

where $\kappa_{r,l}^{0}$ stands for a fixed effect, and $\kappa_{r,l}^{0,C}(t)$ and $\kappa_{r,l}^{0,E}$ stand for climate and ecosystem effects regarding land use l in region r. More precisely, $\kappa_{r,l}^{0,C}(t)$ is null for all land uses except for wheat and maize since both crops are strongly affected by climate change. In this case, the parameter $\kappa_{r,l}^{0,C}(t)$ depends on global climate scenarios. The parameter $\kappa_{r,l}^{0,E}$ is null for all land uses except for oleaginous and permanent crops such as orchards which are strongly affected by ecosystem services. This parameter is supposed constant and the coefficient ν is inferior to 1, highlighting a marginally decreasing impact of ecosystem service E on $\rho_{r,l}^{0}(E_r(t), C_r(t))$. All these parameters are calibrated with data from the ecological literature. A similar function is used to compute the upper bound:

$$\rho_{r,l}^{sup}(E_r(t), C_r(t)) = \kappa_{r,l}^{sup}\left(1 + \kappa_{r,l}^{sup,C}(t) + \kappa_{r,l}^{sup,E} E_r(t)^{\nu}\right) \quad (6)$$

Ecosystems are affected by land uses, pesticides and fertilizers as detailed in the ecological model in Section 2.1.3 thus exhibiting the inter-dependencies between ecological and agro-economic systems.

Second, the maximization of the objective function described in Eq. 1 is subject to 2 technical-economic constraints:

$$\sum S_{r,l}(t) = S_r \quad (7)$$

$$|S_{r,l}(t+1) - S_{r,l}(t)| \le \xi_l S_{r,l}(t) \quad (8)$$

The land availability constraint (Eq. 7) ensures a constant regional area over time. The rigidity constraint (Eq. 8) limits the magnitude of land use change in each period. Similarly to Mouysset et al. (2019), it indirectly accounts for transition costs between two land use classes. As in Mouysset et al. (2019), we do not take into consideration changes in food demand and technological context. Finally, additional technical constraints might regard some specific land uses. In this study, we take two of them in consideration, related to our french case study: the areas of forests and permanent grasslands are bounded by the Natura 2000 network (i.e. a protected area framework in France).

2.1.3 The ecological model

The ecological model is used to predict the overall biodiversity state, proxied by birds population. It is related to a spatially explicit model of metapopulation as in Mouysset et al. (2019). A metapopulation is defined as a network of interconnected subpopulations of a species. Each region r is characterized by a subpopulation driven by two ecological processes: first, the reproduction of individuals within a region, and second, the dispersal between regions. While the dispersion model is strictly identical to Mouysset et al. (2019), innovations are included in the reproduction function due to the effects of pesticides and fertilizers on biodiversity.

The reproduction function (i.e. the intra-regional population dynamics) is modeled using a Verhulst model based on logistic growth:

$$N_{i,r}(t+1) = N_{i,r}(t)\left[1 + r_i \frac{N_{i,r}(t)}{K_{i,r}(t)}\right] \quad (9)$$

where $N_{i,r}(t)$ is the abundance of species i in region r at time t. The parameter r_i represents the intrinsic growth rate of species i and is constant for each species at the national scale. The variable $K_{i,r}(t)$ represents the carrying capacity in region r at time t for species i. The carrying capacity is assumed to be sensitive to land use, inputs and climate variables as follows:

$$\frac{1}{K_{i,r}(t)} = \beta_{i,r}^{0} + \sum_l \beta_{i,l}^{S} S_{r,l}(t) + \sum_l \beta_{i,l}^{P} P_{r,l}(t) + \sum_l \beta_{i,l}^{F} F_{r,l}(t) + \sum_j \beta_{i,j}^{C} C_{r,j}(t) \quad (10)$$

where the parameter $\beta_{i,r}^{0}$ captures a regional fixed effect. This term describes environmental effects which are not included in the other explanatory variables such as altitude. The parameters $\beta_{i,l}^{S}$ stand for the response of species i to the surfaces of land uses l. In contrast to Mouysset et al. (2019), species also respond to pesticides and fertilizers through parameters $\beta_{i,l}^{P}$ and $\beta_{i,l}^{F}$ respectively. Finally, the parameters $\beta_{i,j}^{C}$ stand for the response

of species i to climate variable j. Because land use, input and climate variables ($S_{r,i}(t)$, $P_{r,i}(t)$, $F_{r,i}(t)$ and $C_{r,j}(t)$) vary over time, the carrying capacity $K_{i,r}$ evolves with time, as a function of the environmental context.

Second, we consider an inter-regional dynamic between connected regions in our spatial framework. Individuals can disperse between two regions according to a national species-specific dispersion rate defined as in Mouysset et al. (2019). We assume the dispersal between two connected regions to be symmetric.

2.2 A case study: Metropolitan France

The bioeconomic model presented in the previous section has been calibrated with a French case study. The territory is divided into 707 small agricultural regions (SARs) exhibiting specific environmental characteristics (land use distributions, input use and climate change), biological states (bird abundance) and economic characteristics (profit per hectare).

2.2.1 Land use and input data

Land uses are defined from the European Environment Agency's CORINE Land Cover (CLC) project, focusing on metropolitan France for the years 2000, 2006, 2012 and 2018. The CLC project is a biophysical inventory of land use and its evolution, with a detailed nomenclature in 44 categories. According to the methodology developed in Cocco et al. (2021), we aggregated the nomenclature into six main land uses of interest: urban areas, broadleaves forests, coniferous forests, annual crops, perennial crops, and permanent grasslands. Linear extrapolations are used to estimate data in years between 2000, 2006, 2012 and 2018.

This description of land use is then refined using technical and economic data. Annual crops are split into: cereals (excluding maize and rice), maize, oilseeds, protein crops and temporary grasslands. Perennial crops are differentiated between orchards (including olive groves) and vineyards. Information regarding organic versus conventional farming is included for both annual and perennial crops. To do so, we use data from EIDER and Agreste (former and current statistical databases from the French Ministry of Environment) at the department level for the period 2000–2020, and from Eurostat at the NUTS2 level for the 2 years 2013 and 2016. Specific information for forests is taken from sustainable management labels (PEFC or FSC). Agronomic yield and input use (pesticides and fertilizers) data are derived from the Annual Agricultural Statistics of Agreste. Complementary data are obtained from ADEME and FranceAgrimer reports. The ecosystem service function is calibrated with data from numerous works focusing on the impact of pollination on fruits and rapeseed (Klein et al., 2006; Bommarco et al., 2012; Garratt et al., 2014; Lindström et al., 2015; Geslin et al., 2017; Perrot et al., 2019; Kirchweger et al., 2020). Changes in yield due to climate

change is taken from the European Joint Research Centre's technical report[1] analyzing the impacts of climate change on European agriculture by 2050 (European Commission Research Centre, Joint et al., 2020).

2.2.2 Economic data

Spatially differentiated economic data are used within our bioeconomic model. Agricultural economic data come from the Annual Agricultural Statistics of Agreste, the European database of Eurostat and the European Farm Accountancy Data Network FADN. Specific additional information regarding forests emerges from the French National Forestry Office (NFO). The rigidity parameters are the same as in Mouysset et al. (2019) when applicable, and the others are set with historical data (time series between 2000 and 2019). Such constraints ensure realistic but flexible dynamics of LUC.

2.2.3 Biodiversity data

Common birds are used as a biodiversity metrics since they exhibit many advantages (Ormerod and Watkinson, 2000; Gregory et al., 2004; Sekercioglu et al., 2004). As predators, they capture many changes in the entire food chain. Moreover, they provide ecosystem services (regulation of invertebrates, rodents and natural pest control agents). Birds are deeply affected by changes in land use proportions and less sensitive to landscape structure. Eventually, their close vicinity to humans makes them a simple and comprehensive example of biodiversity for a large audience of citizens.

Data on bird populations are derived from the French Breeding Bird Survey (FBBS), a monitoring program in which trained ornithological volunteers count birds by visual or auditory contact twice a year on the same plot, following a standardized protocol (Jiguet et al., 2012). The period runs from 2001 to 2019 and the collection is organized by the French National Museum of Natural History. FBBS data have already been used in more than 100 international scientific publications, addressing the impact of global changes on bird communities, and solutions to mitigate these impacts. We consider a large group of species breeding in France based on 60 species, split into 3 functional groups based on their habitat preference (Julliard et al., 2006): 14 generalist species, 23 agricultural specialist species, and 23 forest specialist species. The list of species is available in Mouysset et al. (2019). These common species constitute very abundant populations whose areas of distribution cover the whole French territory. It makes it then possible to conduct our analysis at the national scale.

2.2.4 Climate data

The climate data come from Météo France measurement stations, which are spatially interpolated on a regular 8 km grid

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1   https://publications.jrc.ec.europa.eu/repository/

using the SAFRAN surface model. We use the average daily temperature and daily rain precipitation data for the 2000–2020 period to create relevant year-SAR-aggregated ecological variables. The forecast data come from Driaslesfutursduclimat© which provides access to the different climate evolutions simulated for the current century in France.

Many explanatory climate variables can be constructed to assess the impact of climate change on biodiversity. Based on a review of the recent literature on the study of the impacts of climate change on the distribution areas of terrestrial biodiversity and the abundance of species, we selected some relevant variables to capture the average climate trend effects and extreme climate events: Mean Annual Temperature, Cumulative Annual Precipitation, Minimum Temperature of the Coldest Month, Maximum temperature of the Warmest Month, Mean Breeding Season Temperature, Cumulative Breeding Season Precipitation, Number of Extreme Hot Days.

2.2.5 Parameters estimation and variable selection

Following the method described in Mouysset et al. (2019) and Cocco et al. (2021), we calibrate the ecological model over a timeline from 2002 to 2018. Bird abundance was described by land use, input and climate variables according to the equations described in the ecological model section. We performed regression based on the least squares method in R-software and estimated the model coefficients for each species i. However since we added new variables compared to Mouysset et al. (2019), our set of land use, input and climate variables may lead all together to an over-specification of the ecological model despite their individual theoretical relevance. Since we aim at using our model to describe current bird population trajectories but also to predict future trends of bird populations, we proceeded to a variable selection by comparing the goodness-of-fit and the predictive power of different sets of explanatory variables.

Following the methodology described in Mouysset et al. (2016) we used the MAPE (Mean Absolute Percentage Error) as a minimizing criterion since it dampens inter-species population size differences. The goodness-of-fit is computed in-sample: the absolute deviation of the predicted values from the actual values is calculated relative to the actual values over the period 2016–2018, for a model calibrated over the period 2002–2018. The predicted values are estimated recursively from the initialization year 2002. The in-sample period is chosen sufficiently distant in time from the initialization year in order to capture the error amplification effects. The predictive power is computed out-sample: the MAPE is calculated on the same period 2016–2018, but for a model calibrated on the period 2002–2015. The initialization year is also 2002. Based on the *ols_step_best_subset* function in the software R, we developed a new automatic variable selection method adapted to linear panel

models, minimizing the $MAPE_{in}$ and $MAPE_{out}$ indicators. The final selection of models depicted among functional groups (namely the generalist, the farmland and forest specialist species) reported in Supplementary Appendix S6.2 and Figure 2 in Supplementary Appendix S6.3 presents some illustrative examples of predicted versus historical bird dynamics.
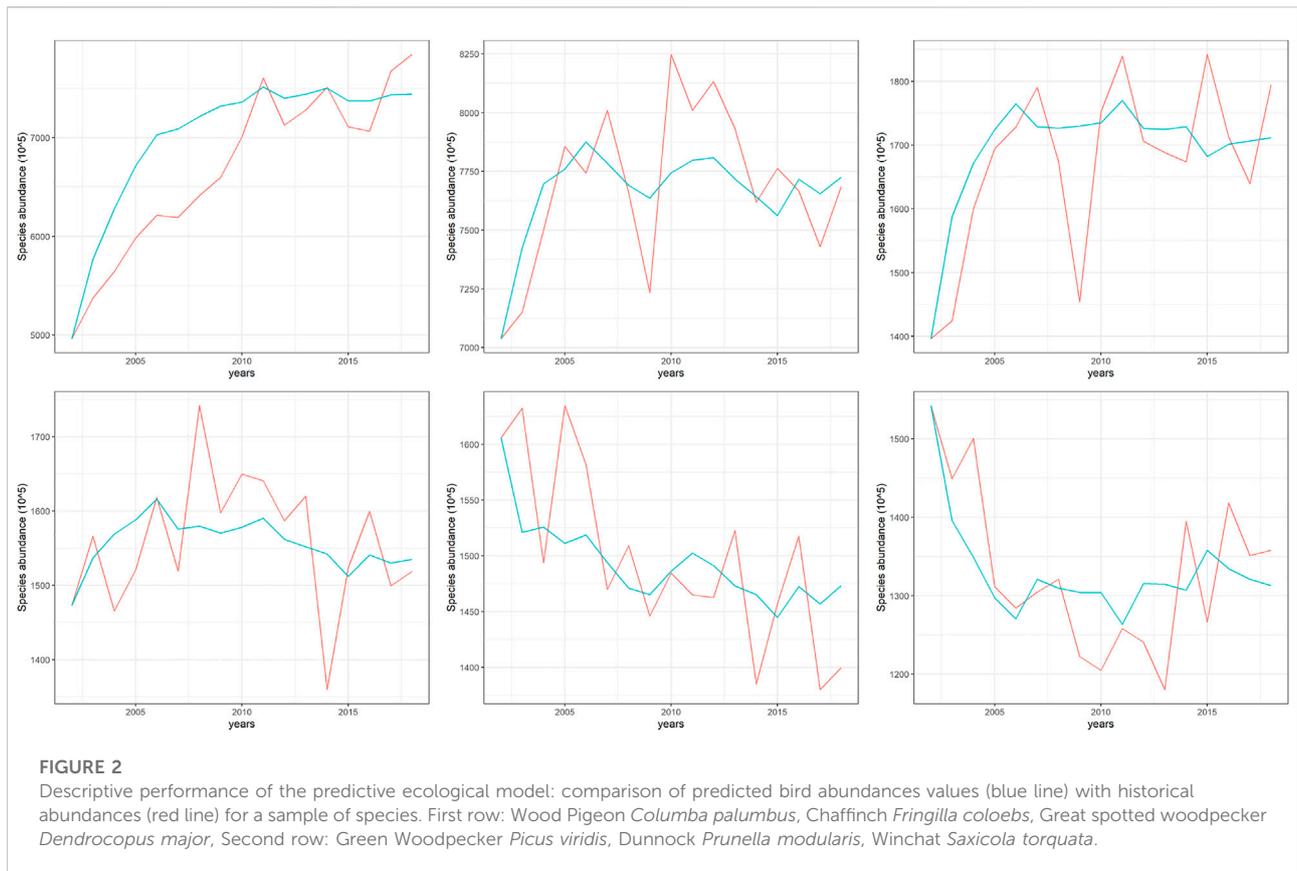
3 Scenarios and indicators

Using this bioeconomic framework, we assess the economic and ecological performances of agricultural landscapes from 2019 to 2050 according to different public policies and climate change scenarios.

3.1 Public policies scenarios

We investigate 4 contrasted scenarios which are compared to a Business As Usual scenario. The 4 contrasted scenarios follow different objectives, either related to a production objective (food or energy goals) or to an environmental objective (focus on pollution or ecosystem). They are detailed below:

- The "Business As Usual" (BAU) scenario pursues current CAP without any additional changes, meaning that the public incentives are equal to zero: $\delta_l = 0$ for all land uses l.
- The "Food" scenario follows a food production objective. To do so, it promotes the expansion of intensive annual crops AC ($\delta_{AC} > 0$) while temporary grasslands GL_T are taxed ($\delta_{GL\_T} < 0$) since the high profitability of the latter makes them competitive to food crops expansion.
- The "Energy" scenario promotes energy production from timber and organic biomass, with underlying motivations to decarbonize the energy mix, increase energy independence, reduce vulnerability to international market fluctuations and develop local energy. It is modeled through subsidies dedicated to productive coniferous forests CF and oleaginous biofuel crops Oil ($\delta_{CF} > 0$ and $\delta_{Oil} > 0$).
- The "Pollution" scenario aims at reducing phytosanitary pressure on ecosystems and promotes less intensive management methods for annual AC and perennial PC crops as well as grasslands GL ($\delta_{AC} > 0$ if $P_{AC} + F_{AC} < T$, $\delta_{PC} > 0$ if $P_{PC} + F_{PC} < T$, $\delta_{GL} > 0$ if $P_{GL} + F_{GL} < T$, where T stands for a given threshold).
- The "Nature" scenario aims at preserving biodiversity and ecosystems by expanding permanent grasslands and broadleaves forests semi-natural habitats. The two land uses benefit from subsidies ($\delta_{GL} > 0$ and $\delta_{BF} > 0$) while temporary grasslands are taxed ($\delta_{GL\_T} < 0$).

FIGURE 2
Descriptive performance of the predictive ecological model: comparison of predicted bird abundances values (blue line) with historical abundances (red line) for a sample of species. First row: Wood Pigeon *Columba palumbus*, Chaffinch *Fringilla coloebs*, Great spotted woodpecker *Dendrocopus major*, Second row: Green Woodpecker *Picus viridis*, Dunnock *Prunella modularis*, Winchat *Saxicola torquata*.

The levels of incentives have been determined in order to obtain a similar inter-annual public budget with the 4 scenarios. It is therefore possible to compare the different scenarios and investigate how to allocate a given public policy envelope to different policy goals. In our study, we chose the overall inter annual envelope of 120 BnEuros, with an average annual budget of 6.5 BnEuros/year. In comparison, nowadays, the French annual CAP budget is 8 BnEuros/year. In our study, we thus investigated a slightly lower budget than the on-going CAP, but we proceeded to a sensitivity analysis with an upper case and an lower case (with higher and lower incentive levels than in the main case).

Table 2 sums up the levels of incentives δ_l we have tested in our study. Regarding the Pollution scenario, we consider the threshold T to be the first tercile of the pollution rate (sum of phytosanitary products) within the historical data.

3.2 Climate scenarios

We choose two contrasted climate scenarios among the widely used Representative Concentration Pathways (RCP). The RCP4.5 which assumes CO2 concentrations stabilization by the end of the century is our benchmark scenario; the more

pessimistic RCP8.5 assumes a growing trajectory of GHG. Data are computed with the model ALADIN 5[2] from the CNRM[3], and we restricted our estimations to the mid-term period 2020–2050. Results are first presented for the climate scenario RCP4.5, then we investigated the robustness of our results to the second climate scenario RCP8.5. Both climate scenarios affect the climate variables that affect bird communities (especially Mean Annual Temperature, Cumulative Annual Precipitations, Maximum Temperature of the warmest month and Cumulative Breeding Season Precipitation) and the ranges of crop yields (ρ^0 and ρ^{sup}) based on JRC prospective studies.

3.3 Indicators

To assess the impact of public policy scenarios on the landscape, we combined a set of 18 indicators which are merged into 4 classes.

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2 Aire Limitée Adaptation dynamique Développement InterNational.

3 Centre National de la Recherche en Météorologie.

TABLE 1 Table of main acronyms as they appear in the main text.

Acronym	Long name
IPCC	Intergovernmental Panel on Climate Change
CAP	Common Agricultural Policy
SAR	Small Agricultural Region
P	Pesticides
F	Fertilizers
CLC	CORINE Land Cover
NUTS	Nomenclature of Territorial Units for Statistics
PEFC	Programme for the Endorsement of Forest Certification
FSC	Forest Stewardship Council
LUC	Land Use Changes
FBBS	French Breeding Birds Survey
BAU	Business As Usual
MAPE	Mean Absolute Percentage Error
AC	Annual crops
PC	Perrenial crops
GL_T	Temporary grasslands
GL	Permanent grasslands
BL	Broadleaves
CF	Coniferous forests
P	Pesticides
F	Fertilizers
RCP	Representative Concentration Pathway
GHG	Green House Gases
JRC	Joint Research Center
GBI	Generalist Bird Index
FBI	Farmland Bird Index
WBI	Woodland Bird Index

A first group of 4 indicators aims at evaluating the biophysical impacts of scenarios in line with their different objectives, both productive and environmental (these indicators are thus called "target indicators"). In regards with the productive targets, we considered an indicator of food production based on calories produced and an indicator of energy production based on the energy derived from timber and biofuels. In regards with the environmental targets, we computed a pollution indicator based on the use of pesticides and fertilizers, and the ecological Community Specialization Index as it emphasizes the specialist species which are more fragile than generalist species in the face of land use and climate changes.

In order to capture other facets of ecosystems, we added another community indicator related to the mean trophic index in the community (namely the Community Trophic Index) as well as abundance indices related to generalist species, farmland specialist species and woodlands specialist species (Generalist Bird Index GBI, Farmland Bird Index FBI, Woodland Bird Index WBI respectively). The integration of abundance indices is

interesting regarding an institutional perspective since the FBI is one of the official ecological indicators of agricultural changes in Europe (Gregory et al., 2005).

A third group of indicators aims at assessing the economic states. We considered both public and private perspectives. Adopting a public point of view, we compute the inter-annual public budget and the inter-annual social welfare of each scenario. By considering the targeted indicators of each scenario, we derived two cost-effectiveness measures of public policies based on budget and social welfare. Following a private perspective, we computed the inter-annual national income of the regional planners over France, their long-term mean income based on their profit in 2050 and the average inequality between regional incomes.

Finally, we investigated a last group of 3 indicators to go further on the climate impacts. In the perspective of a mitigation target, we computed an indicator of carbon stock and an indicator of carbon sequestration flow. We completed these indicators by an ecological indicator related to the community adaptation to temperature change, namely the Community Thermal Index.

Supplementary Appendix S6.4 provides more details about the mathematical computations of these indicators.

4 Results

4.1 Effectiveness of policy scenarios

Table 3 presents the progression of the target indicators for the 4 public policy scenarios (Food, Energy, Pollution and Nature) in comparison with the BAU scenario. We observe that the 4 scenarios are able to improve their related target indicator. In other words, a similar public envelope of 120bn€ is sufficient to increase the 4 objectives. However, the performances are rather heterogeneous among scenarios: the Energy scenario increases bioenergy production by 168% in comparison with BAU, the Food scenario increases food production by 50% in comparison with the BAU, the Pollution scenario diminishes pollution spreading by 21% in comparison with BAU while the Nature scenario improves the specialization of bird communities by 0.94% in comparison with BAU. As a consequence, the public budget cost-effectiveness of the 4 scenarios is strongly contrasted as depicted in row 3 of Table 3.

As expected, the 4 scenarios exhibit a decrease in social welfare (raw 4 in Table 3) in comparison with the BAU. This decrease is smaller for the Energy scenario (1.7%), than the Pollution scenario (3.2%) and than the Food and Nature scenarios which exhibit similar social welfare decreases (4.3%). However considering these decreases in regards with the target indicator, namely with the cost-effectiveness based on social welfare (row 5 in Table 3), the ranking of the scenarios comes back to the one obtained with the budget-based cost-

TABLE 2 Detailed description of public incentives for the 4 public policy scenarios: Food, Energy, Pollution and Nature. The baseline scenarios are supplemented with an upper and lower case (i.e. with higher and lower incentive levels than in the main case). Negative incentives are taxes and positive ones subsidies. Only subsidies of the Pollution scenario impose restriction on the use of phytosanitary products. P stand for pesticides, F for fertilizers, AC for annual cultures, Oil for oleaginous crops, GL_T for temporary grasslands, GL for permanent grasslands, CF for coniferous forests, BL for broadleaves forests.

Scenarios	Public policies	Tax and subsidies schemes
Food	Low	$\delta_{AC} = 550€/ha$ and $\delta_{GL\_t} = -350€/ha$
	Baseline	$\delta_{AC} = 900€/ha$ and $\delta_{GL\_T} = -700€/ha$
	High	$\delta_{AC} = 1{,}250€/ha$ and $\delta_{GL/GL\_T} = -1{,}050€/ha$
Energy	Low	$\delta_{CF} = 700€/ha$ and $\delta_{Oil} = 500€/ha$
	Baseline	$\delta_{CF} = 1{,}000€/ha$ and $\delta_{Oil} = 500€/ha$
	High	$\delta_{CF} = 1{,}300€/ha$ and $\delta_{Oil} = 500€/ha$
Pollution	Low	$\delta_{AC} = 200€/ha$ if $P_{AC} + F_{AC} < T$, $\delta_{PC} = 200€/ha$ if $P_{PC} + F_{PC} < T$, $\delta_{GL} = 200€/ha$ if $P_{GL} + F_{GL} < T$
	Baseline	$\delta_{AC} = 400€/ha$ if $P_{AC} + F_{AC} < T$, $\delta_{PC} = 400€/ha$ if $P_{PC} + F_{PC} < T$, $\delta_{GL} = 400€/ha$ if $P_{GL} + F_{GL} < T$
	High	$\delta_{AC} = 600€/ha$ if $P_{AC} + F_{AC} < T$, $\delta_{PC} = 600€/ha$ if $P_{PC} + F_{PC} < T$, $\delta_{GL} = 600€/ha$ if $P_{GL} + F_{GL} < T$
Nature	Low	$\delta_{GL} = 400€/ha$ and $\delta_{BF} = 400€/ha$ and $\delta_{GL\_T} = -800€/ha$ and $\delta_{AC} = -200€/ha$
	Baseline	$\delta_{GL} = 800€/ha$ and $\delta_{BF} = 800€/ha$ and $\delta_{GL\_T} = -1{,}000€/ha$ and $\delta_{AC} = -400€/ha$
	High	$\delta_{GL} = 1{,}200€/ha$ and $\delta_{BF} = 1{,}200€/ha$ and $\delta_{GL\_T} = -1{,}200€/ha$ and $\delta_{AC} = -600€/ha$

TABLE 3 Overall effectiveness of the 4 public policy scenarios and the BAU. Highlighted values are computed in comparison to the BAU and in regards with the scenarios target indicators, namely Food production for Food scenario, Energy production for Energy scenario, Pollution spreading for Pollution scenario, and Specialization Community Index for Nature scenario. All other indicators read in the specified units and compare across scenarios. For indicators computation details see 6.4.

	Unit	BAU	Food	Energy	Pollution	Nature
Target indicator progression			+50.21 %	+168.47 %	+20.84 %	+0.94 %
Budget	bn€		124	112	119	128
Cost-effectiveness (budget)	%/bn€		0.405	1.503	0.175	0.007
Social welfare	bn€	1,395	1,458	1,482	1,468	1,467
Cost-effectiveness (social surplus)	%/bn€		-0.785	-1.919	-0.282	-0.013

effectiveness. In other words, the Energy scenario is the most cost-effective, followed by the Food one, then the Pollution one and last, the Nature scenario. The stability of this ranking regarding the two cost-effectiveness indicators suggests that it is more effective to achieve productive goals (related to food and energy) than to achieve environmental goals (related to pollution and nature).

Finally, Table 4 in Supplementary Appendix S6.5 shows a robustness analysis of our results based on a sensitivity analysis. We simulate an upper case (the public policy incentives are Lower than in the scenario depicted in Table 3) and a lower case (the public policy incentives are higher than in the scenario depicted in Table 3) for each scenario. This sensitivity analysis confirms the following observations: all the objectives, productive as well as environmental, are achievable with an adequate public

policy, but the productive goals (energy and food) are achieved with more effectiveness than the environmental ones (pollution and nature).

4.2 Cross effects of policy scenarios

Table 5 presents the cross impacts of the 4 public policy scenarios in regards with BAU on the performances related to the 4 objectives: food (food production), energy (energy production), pollution (pollution indicator) and nature (community specialization index). We observe that no scenario is able to increase simultaneously the whole set of performance indicators.

However some main results emerge from Table 5. First, food production, except within the Food scenario, always decreases

TABLE 4 Sensitivity analysis of overall effectiveness of the 4 public policy scenarios, based on a public policy incentive lower case and a public policy incentive upper case (see tab.2). Highlighted values are computed in comparison to the BAU and in regards with the scenarios target indicators, namely Food production for Food scenario, Energy production for Energy scenario, Pollution spreading for Pollution scenario, and Specializing Community Index for Nature scenario. All other indicators read in the specified units and compare across scenarios.

	Unit	BAU	Food_low	Food_high	Energy_low	Energy_high	Pollution_low	Pollution_high	Nature_low
Target indicator progression			+26.60 %	+68.58 %	+137.44 %	+187.95 %	+7.64 %	+25.00 %	+0.61 %
Budget	bn€	0	61	215	85	139	42	210	10
Cost-effectiveness (budget)	%/bn€		0.434	0.319	1.623	1.351	0.180	0.119	0.060
Social welfare	bn€	1,395	1,372	1,284	1,373	1,365	1,386	1,314	1,374
Cost-effectiveness (social surplus)	%/bn€		1.201	0.621	6.313	6.440	0.947	0.311	0.030

TABLE 5 Crossed marginal impacts of the 4 public policy scenarios in regards with the BAU on the 4 main objectives, namely: food production, energy production, pollution spread, Community Specialization Index. Indicators levels of the BAU are expressed in the specified unit for reference, while highlighted values are computed in comparison to the BAU. Table reads as follow: food production level in the Food scenario is 50% higher than in the BAU scenario.

	Unit	BAU	Food	Energy	Pollution	Nature
Food production	TCal	261.22	+50.21 %	-18.36 %	-28.80 %	-22.34 %
Energy production	ktep	4,197.98	-2.05 %	+168.47 %	-24.49 %	-35.46 %
Pollution indicator	Mtons	42.09	+18.83 %	+0.19 %	-20.84 %	-14.30 %
Community Specialization Index		2.44	+1.71 %	+0.39 %	-0.13 %	+0.94 %

TABLE 6 Crossed marginal impacts of the 4 public policy scenarios in regards with the BAU on ecological indicators. Indicators levels of the BAU are given for reference. Note that all indicators are dimensionless (for indicators computation details see 6.4). Table reads as follow: the Food scenario increases the Community Specialization Index by 1.71% in comparison to the BAU.

	BAU	Food	Energy	Pollution	Nature
Community Specialization Index	2.44	+1.71 %	+0.39 %	-0.13 %	+0.94 %
Community Trophism Index	5.65	-0.78 %	-0.10 %	-0.08 %	-0.78 %
Generalist Index	1.22	-5.48 %	+0.75 %	-0.93 %	-3.08 %
Farmland Specialist Index	1.43	-3.15 %	+2.02 %	+1.14 %	-3.05 %
Woodland Specialist Index	1.30	+2.09 %	+2.15 %	+3.78 %	+1.64 %

compared to the BAU scenario. This suggests an antagonism between the two productive goals, namely food and energy, as well as an antagonism between the food goal and the two environmental goals (pollution and nature). Second, we observe that one of the production-oriented scenarios, the Energy scenario, is quasi-neutral regarding pollution spread (+0.19% of pollution compared to BAU) and increases the ecological indicator. This second result suggests that productive performance improvement does not systematically jeopardize environmental performance. The positive effect of this production-oriented scenario on the ecological indicator is explained by the fact that forest expansion provides refuges and shelters nesting areas for most vulnerable species. The very slight excess of pollution might come from the

relatively higher intensity of the crop mix in phytosanitary products. Forest cover expands predominantly over low intensity farming and subsidized oleaginous crops make an intensive use of pesticides and fertilizers. Third, we exhibit a third result as a corollary of the second result: the Energy scenario avoids the overall largest deterioration of performances of the landscape. Except its negative impact on food production, the Energy scenario looks indeed either positive or neutral. Regarding its negative impact on food production, it is nonetheless the least negative impact among the non-food targeted scenarios. As a consequence, the Energy scenario offers an interesting compromise between the different goals of agricultural public policies.

TABLE 7 Marginal impacts of the 4 public policy scenarios on private economic indicators. Indicators levels of the BAU are expressed in the specified unit for reference, while highlighted values are computed in comparison to the BAU. Table reads as follow: Food scenario increases by 4.59% the interannual income in comparison to the BAU. Shades of green indicate a positive evolution while shades of pink indicate a negative evolution.

	Unit	BAU	Food	Energy	Pollution	Nature
Interannual income	bn€	1,394.52	+4.59 %	+6.29 %	+5.30 %	+5.18 %
Long-term income	bn€	113.75	-2.89 %	+2.99 %	+2.51 %	-2.00 %
Inequalities	M€	261.05	-3.59 %	+0.14 %	+0.41 %	-5.62 %

4.3 Ecosystem focus

To further on the ecological side, Table 6 presents the performances of the BAU and the 4 policy scenarios with respect to our 5 ecological indicators. We observe that no scenario is positive for all the dimensions of ecosystems. Surprisingly, the Nature scenario presents a poor overall ecological performance since 3 ecological indicators are declining and 2 of them (Farmland Bird Index and Generalist Bird Index) do so quite strongly. The decrease in arable land and temporary grassland leading to scarcer food resources in the Nature scenario might explain the decline in generalist and farmland bird species. This result suggests that semi-natural habitats expansion as supported in the Nature scenario succeeds in protecting the most vulnerable species by providing them with refuges but should be thought in relation to other ecosystem facets.

On the contrary, the Energy and Pollution scenarios appear as interesting perspectives for ecosystems since they present well-balanced ecological performances. Both of them limit their environmental footprint with the decline of intensive farming, favoring the development of high quality habitats (grasslands for the Pollution scenario and forests for the Energy scenario), along with the massive reduction of phytosanitary products use in the case of the Pollution scenario.

Finally, Table 6 reveals that woodland specialist species seem to benefit from all scenarios. This is explained by the fact that they strongly react to both the decrease in inputs use (pesticides and fertilizers) and forest expansion, whatever its composition.

4.4 Economic focus

Table 7 focuses on economic performances by considering the private agent perspective. As expected with scenarios with overall positive incentives, the intertemporal profit is larger than under BAU for the 4 policy scenarios (+5–6% in average). While this effect exhibits similar intensity for the 4 scenarios, contrasted long-term trends appear. On the one hand, the Food and Nature scenarios generate losses in long-term profit. This is due to the growing impact of taxes: despite a fairly high tax base, the tax is not sufficient to reverse the evolution of temporary grasslands.

On the other hand, the Energy and Pollution scenarios both preserve long-term profits. Subsidized land uses had an original marginal profitability not far from the competing areas within the same region. Since subsidies are all the more profitable for private landowners as the original marginal profitability gaps are reduced, this preserves long-term incomes and hampers social welfare loss.

Contrasted performances are also observed regarding inequalities: while Food and Nature scenarios severely decrease inequalities, the Energy and Pollution scenario both slightly increase inequalities. Regions that were initially the least profitable (usually those with more semi-natural habitats and less crops) benefit from a catch-up effect with the Nature scenario that favors grasslands and broad-leaves forests. In addition, both Food and Nature contribute to regional incomes standardization by a "redistribution process": taxes affect mainly the originally most profitable regions whereas subsidies are directed towards originally least profitable regions. In contrast, the Energy and Pollution scenarios favor regions whose activities were originally not less profitable than average. Clustering scenarios based on their performances in terms of long-term profit and inequalities yields two groups with opposite behaviors. On the one hand, the Food and Nature scenarios, which decrease long-term profit but reduces inequalities. On the other hand, the Energy and Pollution scenarios, which increase long-term profit but increases inequalities. This observation suggests a trade-off between long-term profit and inequalities.

4.5 Impact of climate change

Table 8 investigates the impact of the public policy scenarios on the climate change adaptation indicators, namely the two climate mitigation indicators: Carbon Storage and Carbon Sequestration Flow, and the Community Thermal Indicator for the ecological side. First, we observe that the Energy and Nature scenarios yield particularly positive results regarding climate change mitigation: the impact on both carbon stock and flow is strongly positive. This is not surprising as these scenarios promote the expansion of grasslands and forests, two land uses with a high positive impact on climate change mitigation. On the contrary, the performances of the Food

TABLE 8 Marginal impacts of the 4 public policy scenarios on the climate adaption indicators: two climate mitigation indicators and a metric of birds population adaptation to climate change. Indicators levels of the BAU are expressed in the specified unit for reference, while highlighted values are computed in comparison to the BAU. Note that the CTI is dimensionless. Table reads as follow: Food scenario diminishes by 4.59% the carbon stockage in comparison to the BAU. Shades of green indicate a positive evolution while shades of pink indicate a negative evolution.

	Unit	BAU	Food	Energy	Pollution	Nature
Carbon Stockage	MtCO2eq	11,527.68	-2.49 %	+8.82 %	-0.91 %	+8.46 %
Carbon Sequestration Flux	MtCO2eq/an	21.31	-20.81 %	+51.28 %	-3.94 %	+73.98 %
Community Thermal Index		11.77	-0.17 %	-0.37 %	-0.07 %	-0.18 %

TABLE 9 Overall effectiveness and marginal impacts of the 4 public policy scenarios on the whole set of indicators under the RCP8.5 scenario. Indicators levels of the BAU are expressed in the specified unit for reference, while highlighted values are computed in comparison to the BAU. Red boxes stress values for which the evolution is of the opposite sign of marginal impacts under the RCP4.5 scenario.

	Unit	BAU	Food	Energy	Pollution	Nature
Budget	**bn€**		**124**	**112**	**120**	**129**
Cost-effectiveness (budget)	**%/bn€**		**0.404**	**1.530**	**0.176**	**0.011**
Social welfare	**bn€**	**1,394**	**1,333**	**1,368**	**1,347**	**1,341**
Cost-effectiveness (social surplus)	**%/bn€**		**0.820**	**6.460**	**0.454**	**0.026**
Food production	TCal	260.44	+50.17 %	-17.82 %	-28.24 %	-21.63 %
Energy production	ktep	4,192.07	-0.38 %	+170.82 %	-23.87 %	-33.38 %
Pollution indicator	Mtons	41.95	+18.87 %	+1.13 %	-21.18 %	-13.93 %
Community Specialization Index		2.45	+1.81 %	+0.12 %	-0.04 %	+1.39 %
Community Trophism Index		5.68	-1.02 %	-0.15 %	-0.06 %	-0.83 %
Generalist Index		1.22	-6.79 %	-0.18 %	-1.49 %	-4.16 %
Farmland Specialist Index		1.47	-4.17 %	-0.31 %	-0.20 %	-4.13 %
Woodland Specialist Index		1.32	+0.57 %	+0.81 %	-1.56 %	-0.45 %
Interannual income	bn€	1,393.99	+4.52 %	+6.11 %	+5.28 %	+5.43 %
Long-term income	bn€	113.86	-2.75 %	+2.80 %	+2.42 %	-1.75 %
Inequalities	M€	261.93	-3.81 %	-0.24 %	+0.39 %	-4.97 %
Carbon Stockage	MtCO2eq	11,520.15	-2.20 %	+8.85 %	-0.82 %	+8.75 %
Carbon Sequestration Flux	MtCO2eq/an	21.21	-18.68 %	+51.72 %	-4.37 %	+75.41 %
Community Thermal Index		11.79	-0.06 %	-0.34 %	-0.17 %	-0.49 %

and Pollution scenarios are worse than in the BAU scenario. Second, regarding the thermal index, all scenarios have a negative impact while remaining weak. This indicates that the impact on the "cold" species is slightly stronger than the impact on the "hot" species. Third, the Nature scenario exhibits good performances on carbon mitigation, intermediary performances on ecological adaptation and small changes on the community thermal index. It might be a better compromise regarding climate change in the RCP 4.5 than the Energy scenario which is quasi-neutral regarding climate issues.

Table 9 presents the performances of the BAU and the 4 policy scenarios under a more severe climate change scenario assuming higher CO2 emission (RCP8.5). Performances in the opposite direction of those obtained with climate scenario RCP4.5 are in red boxes. Generally speaking, we observe that few performances are going in a different direction under this stronger climate change scenario. More precisely, the 4 policy scenarios improve their target indicator in a similar way with the two climate change scenarios. For the Energy, Pollution and Nature scenarios, the targeted performances are slightly

increased with climate scenario RCP 8.5 while they are very slightly decreased for the Food scenario. While the target indicator in the Nature scenario only weakly improves, this maps to a non-negligible marginal impact in terms of budgetary cost-effectiveness: it increases by 57%. Despite this effect, the Nature scenario remains the least cost-effective among the 4 we investigated in this study.

The ecological indicators depict the highest differences compared to other indicators. Impacts on ecosystems are contrasted with an overall negative impact on bird abundance and community structure. Especially, the Generalist Bird Index, the Farmland Bird Index and the Community Trophic Index are declining with the RCP8.5 climate scenario whatever the policy scenarios. The impact of the policy scenarios on the Woodland Bird Index, which was always positive with the RCP4.5, becomes more contrasted since the two environment-targeted scenarios (Pollution and Nature) decrease the indicator under the RCP8.5 climate scenario. Generally speaking, climate change does not have monotonous marginal impact on ecological indicators since some of them tend to decrease under RCP8.5 (like the Generalist Bird Index) while some others tends to increase (like the Community Specialization Index). Focusing on economic performances, the impact of climate change is very slight. Even for the impact of the Energy scenario on inequalities, which becomes negative with RCP8.5: the marginal impact is actually small and close to 0.

However, the overall impact of increasing climate change is negative, by decreasing private economic performances. Finally, similar conclusions are obtained regarding the climate change mitigation indicators even if the negative impact of the Food and Pollution scenarios on carbon indicators is less negative under RCP8.5. The impact on thermal indicator remains negative for all scenarios, but we can note that the Nature scenario exhibits the worst results. In a RCP 8.5 context, no scenario looks to be a good compromise to satisfy the 3 climate change mitigation indicators.

5 Discussion

5.1 Synthesis of results

All 4 public policy scenarios succeed in improving their related target indicator with a similar public enveloppe of 120bn€. However, their performance are rather heterogeneous and depict strongly contrasted budget cost-effectiveness. Interestingly, the analysis through budget-based cost-effectiveness and social-based cost-effectiveness rank the scenarios in the same order: Energy and Food first, followed by the Pollution scenario and last, the Nature scenario. This would suggest a greater effectiveness in achieving productive goals than environmental goals. We confirm the robustness of this ranking with a sensitivity

analysis based on scenarios with upper and lower public incentives than the initial ones.

The overall good performance of scenarios should not hide that any of them is able to increase simultaneously the whole set of performance indicators. We reveal different antagonisms: productive goals (food and energy) cannot be achieved concomitantly, but, if productive food goals lower environmental outputs, energy productive performance does not systematically jeopardize environmental performance, as witnessed by increases in specific ecological indicators. All in all, the Energy scenario avoids the overall largest deterioration of performances of the landscape and thereby appears to be an interesting compromise between the different goals of agricultural public policies.

The overall positive incentives increase the intertemporal profit from the private agent perspective. Long-term trends in private profits are more contrasted: losses in long-term profits for the Food and Nature scenarios can be explained by the incapacity of taxes to reverse the evolution of the highly profitable temporary grasslands. On the contrary, subsidies schemes of the Pollution and Energy scenarios preserve long-term incomes and hamper social welfare loss. The two same clusters emerge from the contrasted performances in terms of inequalities. However, Food and Nature here contribute to regional incomes standardization by a "redistribution process", while Energy and Pollution favor regions whose activities were originally not less profitable than average. This would suggest a trade-off between long-term profit and inequalities.

Antagonisms exist among the multiple dimensions of ecosystems and no scenario is able to positively increase all ecological indicators. Surprisingly, the Nature scenario presents a poor overall ecological performance, as food resources allegedly diminish. In contrast, the Energy and Pollution scenarios present well-balanced ecological performances by favoring the expansion of high-quality habitats or achieving massive reductions in phytosanitary products use.

Regarding climate change, scenarios promoting the expansion of high soil-CO_2-content land uses, such as Nature and Energy scenarios, unsurprisingly increase carbon storage and carbon sequestration flow, thereby favoring climate change mitigation. For a general assessment, most previous results stand when assessed under a more severe climate change scenario. Notably, the 4 policy scenarios improve their target indicator in a similar way with the two climate change scenarios. Only the ecological indicators show contrasted performance with an overall negative impact on bird abundance and community structure. No scenario can restrain the drop in generalists and farmland birds population, and in the Community Trophic Index. However, climate change does not have a monotonous marginal impact on ecological indicators since some also tend to increase, as the Community Specialization index. Lastly, none of

the scenarios prevent the slight decrease in economic performance due to more severe climate conditions, nor appear to be a good compromise to satisfy the 3 climate change mitigation indicators.

5.2 Implications for agricultural public policies

First, our results show that it is possible to achieve productive and environmental goals with the on-going budget of European agricultural policy. This conclusion opens stimulating challenges about which strategy to implement in designing agricultural policies, specifically when considering expectations about biodiversity issues (Pe'er et al., 2019; Pe'er and Lakner, 2020; Pe'er et al., 2020; Candel et al., 2021). As an encouraging perspective, we highlighted that synergies between productive and environmental performances of agricultural landscapes do exist, meaning that they can be improved *simultaneously* compared to the current situation. These synergies are nevertheless not trivial nor systematic since some productive goals remain antagonistic with some environmental goals. A fine analysis of the variety of agricultural policy goals is thus required.

Our study shows that 1) the food-oriented goal seems to be particularly orthogonal with the other dimensions of agricultural policy targets, namely the energy and environmental ones, and 2) a grassland-oriented policy (here the Nature scenario) is antagonistic to productive goals. These results bring new significant explanations to the current locking of the European agricultural public policy: by coupling a historically food-dedicated first set of incentives (e.g the "first pillar") with a second set of environment-targeted incentives historically promoting semi-natural habitats (e.g "the second pillar"), the structure of the European CAP looks therefore inevitably inefficient. Our study allows to go a step further on the tension between the two pillars of the current CAP. Indeed, we showed a high contrast in cost-effectiveness to achieve the different public policy targets. More specifically, the food target is achieved with a very high cost-effectiveness while the ecological target driven by semi-natural habitat promotion is achieved with a very small one. Such an imbalance necessarily makes the environmental targets less attractive in regards with the productive ones. It might hamper the re-balancing of the CAP budget from the historical productive incentives towards environmental incentives. We therefore understand how particularly fertile the European agricultural policy is for high frustrations (Erjavec and Erjavec, 2015; Alons, 2017; Hennig and Breustedt, 2018; Bengtsson et al., 2019; Hristov et al., 2020) and hot negotiations (European Commission, 2018; Court of Auditors, 2019). In this context, we support that exploring potential synergies between the alternative productive and environmental goals constitutes the only perspectives to design sustainable agricultural public policies in Europe.

In consistency with two recent European reports (Wissenschaftliche Beiräte, 2017; European Commission et al., 2019), our study highlighted that an agricultural public policy which focuses on energy production might offer an interesting compromise regarding the different facets of agricultural landscapes. Indeed, energy provision performance improvement does not systematically jeopardize environmental performances since our energy-targeted scenario presents well-balanced ecological performances and generates almost no pollution change. Moreover, food production reduction remains limited. Regarding the economic side, the public cost-effectiveness is high and the impact on private income is either positive or neutral. Eventually, this scenario is a satisfying strategy regarding carbon-based climate change mitigation indicators. Our study allowed to complete this result by pointing to a credible environment-oriented alternative to the actual production-oriented policy. Indeed, the pollution scenario constitutes an overall well-balanced strategy suggesting that environmental issues should be faced by the pollution reduction commitment instead of a land use change objective (as in the Nature scenario). Nevertheless, we have to keep in mind that an environment-oriented policy generates smaller synergies than an energy-oriented one since it is slightly less competitive regarding both the ecological and economic sides.

Interestingly, our conclusions look robust to climate change contexts if we consider highly probable climate change scenarios (here RCP 4.5 and RCP 8.5). In other terms, adequate agricultural public policies might attenuate climate change effects when considering intermediary climate change scenarios. Our study specified that this effect might come from either a land use distribution effect or an input use effect, thus highlighting two potential levers to deal with climate issues in agricultural policies (Dunford et al., 2015; Mouchet et al., 2017; Pe'er and Lakner, 2020).

However, we have to note that the climate scenarios investigated in this study are based on moderate climate changes. Due to non-monotonous effects on agricultural systems and ecosystems (Peters et al., 2019; Pörtner et al., 2021), different conclusions might emerge with stronger climate change effects. Eventually, bio economic projections should be conducted at a longer-term simulation window to the 2,100 time horizon. Indeed, these scenarios are expected to exhibit stronger divergences by the end of the century.

5.3 The bioeconomic modeling framework to investigate future global changes

This paper presents an interdisciplinary study based on a bioeconomic model integrating complex interdependencies between ecosystems and human society (Jean and Mouysset, 2022). Despite divergences between economic and ecological

disciplines (Drechsler, 2020), this kind of bioeconomic framework offers the holistic view required to investigate the trade-offs between ecosystem services provided by agricultural landscapes in a context of climate change (Bateman et al., 2013; Oliver and Morecroft, 2014; Mouysset et al., 2019; Rosa et al., 2020). Based on mechanistic process-based ecological and economic equations, this approach avoids the monetary evaluation of biodiversity, which is controversial (Diamond and Hausman, 1994). The precision required to integrate agronomic, economic, ecological and climate data compensates for the relatively simple formalism of the model and makes it possible to obtain robust and informative results to investigate prospective scenarios and to understand the future impacts of global changes.

The results are however strongly dependent on methodological choices. For example, the profit-maximizing assumption in our model implies that the most profitable land uses will necessarily be chosen at the expense of the less profitable ones. But in the real world, land use changes are also driven by risk aversion (Lien, 2002). This economic mechanism has shown positive and determinant impact on agricultural bioeconomic performances (Mouysset and Doyen, 2013).

Indeed, diversification driven by risk aversion has positive impacts on ecosystems (Lehman and Tilman, 2000; Roscher et al., 2009; Isbell et al., 2011; Cardinale et al., 2012) and ecosystem services provision (Robinson and Sutherland, 2002; Laiolo, 2005; Quaas et al., 2007). Moreover, our economic model does not include explicit spatial processes such as neighborhood effects, despite some considerations for spatial heterogeneity. From these neighborhood phenomena, we could expect positive effects by expanding good practices, or on the contrary deleterious effects by slowing down their expansion through collective inertia (Wollni and Andersson, 2014). The overall effect on the effectiveness of public policy is thus non-trivial while being possibly determinant.

Regarding the climate change impact, we considered only linear effects between land use and climate changes within ecological models. Yet, the mutual impacts of these two global changes look non-linear and complex with expected threshold effects (Oliver and Morecroft, 2014; Elmhagen et al., 2015; Peters et al., 2019). In this context, complexifying the ecological model would be required by incorporating second order effects of climate variables as well as cross-effects between land use and climate variables. Moreover, the lack of an explicit modeling of the direct effects of climate on carbon sequestration services may lead to an underestimation of climate change impacts. Indeed, climate change modifies land use patterns that indirectly affect carbon stock by replacing high-CO2-content land uses by low ones. But future warming could also directly and significantly reduce the carbon storage capacities of soils and biomass (Álvaro-Fuentes et al., 2012). With a medium-term prospective window, we cannot apprehend the diminishing efficiency of carbon sequestration due to saturation of the carbon sink at some point.

For the agronomic side, the linearity of the crop response function bounded by an upper threshold only approximate the real response function, closer to a concave curve model featuring diminishing marginal yield with respect to inputs. It further implies quasi-perfect substitution between inputs while pesticides and fertilizers serve specific purposes: eliminate weeds and undesirable organisms for the former, and provide plants with nutrients for the latter.

5.4 Future research avenues

We propose here avenues for future research, regarding the 2 facets of our bioeconomic framework, the economic and ecological ones.

Regarding the economic perspective, it would be very informative to connect such nation-based studies with a broader framework. Indeed, both climate issues and market dynamics exhibit large-scale drivers, at least at the European scale. Considering large-scale supply and demand balancing as well as European reallocation of resources by exploiting the comparative advantages of countries might help to design endogenous adaptation to climate change (Dunford et al., 2015; Mouchet et al., 2017; European Commission Research Centre, Joint et al., 2020). At the same time, refining nation-based bioeconomic frameworks to a smaller scale could be required to address the question of inequalities. Spatialized public policies might thus be assessed to take into account the heterogeneous regional adaptation capacity depending on capital and resources (Dunford et al., 2015; Nicholas et al., 2020). Investigations in this direction would be informative for the debate on targeted-area measures such as Climate and Agri-environmental Schemes.

Regarding ecosystems, a natural perspective is to deepen the representation of biodiversity, consistently with Rosa et al. (2020), who calls for the integration of specific functional traits of biodiversity and for an expanded coverage of the multiple dimensions of biodiversity and ecosystem services. As many taxa are impacted by climate change and land use changes (Martin et al., 2013; Visconti et al., 2015), their inclusion would provide more accurate information on the general level of vulnerability of ecosystems. It would notably open the possibility of modeling interspecies interactions within food webs which are determinant regarding the risk of extinction due to climate and land use drivers (Holyoak and Heath, 2016). As some species are more impacted by polluting uses, especially those in freshwater ecosystems (Bayramoglu et al., 2019), their inclusion could be an additional argument in favor of environmentally friendly policies. In regards, the retroactive effects of biodiversity on land use changes (through pollination, natural control of pathogens, and pollution control), could be better modeled if the ecological functionalities of biodiversity (stemming from

its abundance, richness and functional diversity) were clarified (Gagic et al., 2017; Dainese et al., 2019; Woodcock et al., 2019).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Author contributions

All authors contributed to handling the manuscripts and writing this editorial, and approved it for publication.

Acknowledgments

Such studies would not be feasible without the dedicated help of hundreds of volunteers monitoring bird communities across the country yearly.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.889506/full#supplementary-material

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