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From Population Viability Analysis to Coviability of Farmland Biodiversity and Agriculture

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Abstract: *Substantial declines in farmland biodiversity have been reported in Europe for several decades. Agricultural changes have been identified as a main driver of these declines. Although different agrienvironmental schemes have been implemented, their positive effect on biodiversity is relatively unknown. This raises the question as to how to reconcile farming production and biodiversity conservation to operationalize a sustainable and multifunctional agriculture. We devised a bioeconomic model and conducted an analysis based on coviability of farmland biodiversity and agriculture. The coviability approach extended population viability analyses by including bioeconomic risk. Our model coupled stochastic dynamics of both biodiversity and farming land-uses selected at the microlevel with public policies at the macrolevel on the basis of financial incentives (taxes or subsidies) for land uses. The coviability approach made it possible for us to evaluate bioeconomic risks of these public incentives through the probability of satisfying a mix of biodiversity and economic constraints over time. We calibrated the model and applied it to a community of 34 common birds in metropolitan France at the small agricultural regions scale. We identified different public policies and scenarios with tolerable (0–0%) agroecological risk and modeled their outcomes up to 2050. Budgetary, economic, and ecological (based on Farmland Bird Index) constraints were essential to understanding the set of viable public policies. Our results suggest that some combinations of taxes on cereals and subsidies on grasslands could be relevant to develop a multifunctional agriculture. Moreover, the flexibility and multicriteria viewpoint underlying the coviability approach may help in the implementation of adaptive management.*

Keywords: bioeconomics, farming, French bird breeding survey, land-use modeling, public policies, viability

Del Análisis de Viabilidad Poblacional a la Co-Viabilidad de la Agricultura y la Biodiversidad de las Tierras de Cultivo

Resumen: *Se han reportado disminuciones sustanciales en la biodiversidad de las tierras de cultivo en Europa durante varias décadas. Los cambios agrícolas han sido identificados como los principales conductores de estas disminuciones. Aunque se han implementado diferentes esquemas agro-ambientales, su efecto positivo sobre la biodiversidad es prácticamente desconocido. Esto genera la pregunta de cómo reconciliar la producción agrícola y la conservación de la biodiversidad para operar una agricultura sostenible y multifuncional. Diseñamos un modelo bioeconómico y realizamos un análisis basado en la co-viabilidad de la biodiversidad de las tierras de cultivo y la agricultura. El acercamiento a la co-viabilidad extendió los análisis de viabilidad de población al incluir riesgos bioeconómicos. Nuestro modelo acopló dinámicas estocásticas tanto de la biodiversidad y el uso de suelo de la agricultura en un micro-nivel, como de las políticas públicas en un macro-nivel con base en los incentivos financieros (impuestos o subsidios) para el uso de suelo. La aproximación de co-viabilidad nos permitió evaluar los riesgos bioeconómicos de estos incentivos públicos a través de la probabilidad de una mezcla satisfactoria de biodiversidad y restricciones económicas a lo largo del tiempo. Calibramos el modelo y lo aplicamos a una comunidad de 34 especies de aves comunes en la Francia metropolitana con la escala de regiones agricultoras pequeñas. Identificamos diferentes políticas públicas y escenarios con riesgo agroecológico tolerable (0-0%) y modelamos sus resultados*

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hasta el año 2050. Las restricciones presupuestales, económicas y ecológicas (basado en Farmland Bird Index) fueron esenciales para entender el conjunto de políticas públicas viables. Nuestros resultados sugieren que algunas combinaciones de impuestos sobre cereales y subsidios sobre pastizales podrían ser relevantes para desarrollar una agricultura multifuncional. Además, la flexibilidad y el punto de visto de criterios múltiples subyacentes al acercamiento de co-viabilidad puede ayudar en la implementación de un manejo adaptativo.

Palabras Clave: bioeconomía, censo de reproducción de aves francesas, modelado, políticas públicas, tierras de cultivo, uso de suelo, viabilidad

Introduction

Modern agriculture and associated intensification of agricultural practices have been identified as major drivers of the decline of farmland biodiversity (Krebs et al. 1999). In this context, the need to reconcile economic and conservation objectives in a sustainable way for agriculture is a major issue.

The importance of the public policies to achieve this goal has been highlighted in Alavalapati et al. (2002), Shi and Gill (2005), Mouysset et al. (2011). Public policies can potentially modify farmers' choices in terms of land uses and practices and thus affect both the ecosystem and the dynamics of biodiversity (Doherty et al. 1999; Holzkamper & Seppelt 2007). Many public policies, including agrienvironmental schemes (AES), have been proposed by decision makers in Europe as a complement to the historical European Common Agricultural Policy (CAP), which strongly supports use of arable land. AES, as developed in the "second pillar" of the CAP, are now considered to be the most important tools to reverse the decline of biodiversity in farmlands (Donald & Evans 2006). However, 15 years after the initial implementation of such instruments at a large scale, their ability to enhance biodiversity remains in question (Vickery et al. 2004; Butler et al. 2009). Indeed, they too often focus on few species (Benton et al. 2003) or fail to yield sufficient effects at a large scale (Kleijn et al. 2001). Hence, conservation and sustainable management of farmland biodiversity still constitute difficult scientific challenges.

To deal with such agroecological issues, we propose a bioeconomic model for use in analyzing public-policy scenarios. Many of the bioeconomic modeling frameworks are problematic because they rely on optimal-control theory. In particular, cost-benefit methods require quantification of biodiversity in monetary terms (Drechsler 2001). Although pricing techniques such as contingent valuation are available, their suitability for biodiversity is disputed (Diamond & Hausman 1994). In this context, the cost-effectiveness approach which avoids the need for monetary evaluation of environmental goods (Gatto & De Leo 2000) by considering biodiversity targets or constraints in nonfinancial terms while optimizing economic values, appears to be a relevant alternative. Results of cost-effectiveness studies usually show a negative trade-off between ecological and economic performances of agriculture (Polasky et al. 2005; Drechsler et al. 2007; Barraquand & Martinet 2011).

We did not focus on the optimal trade-off between biodiversity and agriculture; instead, we adopted a bioeconomic viability or coviability viewpoint for the analysis of public policies and incentives. By *coviability* we mean the simultaneous satisfaction of different constraints related to different points of view. Such a framework is a relevant modeling approach for sustainability (Doyen & Martinet 2012) and is especially useful for balancing apparently contradictory bioeconomic goals (Baumgärtner & Quaas 2009). More generally the viability approach (Aubin 1990) aims at identifying desirable combinations of states and controls that ensure proper functioning of the system. This approach does not aim to identify optimal paths for the codynamics of resources and exploitation; instead, it provides acceptable trajectories that satisfy different kinds of constraints over time. The viability framework has been applied to natural resource management, bringing together socioeconomic and ecological constraints, and especially to the management of renewable resources and fisheries (Béné et al. 2001; Eisenack et al. 2005; Péreau et al. 2012). Links between the coviability approach and population viability analysis (PVA) used in conservation biology (Morris & Doak 2002) and focused on extinction risk is emphasized by Doyen et al. (2012). Specific applications of coviability analysis of agroecological issues can be found in Sabatier et al. (2012), but they do not provide economic insight.

We applied the coviability framework in the context of agriculture, land-use, and terrestrial biodiversity management. In particular, we examined the role of monetary public policies in the sustainable balance between conservation goals and economic requirements. Our analysis of the viability of agricultural public-policy scenarios relied on a bioeconomic model inspired by Mouysset et al. (2011, 2012*b*, 2013). It articulates, in a stochastic and multiscale context, 3 components: biodiversity community dynamics, farming land uses, selected by a group of heterogeneous farmers (i.d. with different characteristics) at the micro-(landscape) level, and macrofinancial incentives. We applied the model to a metropolitan France case study. The coviability approach allowed us to evaluate the bioeconomic risk of public incentives, defined by the probability of satisfying a set of ecological and economic constraints up to the year 2050. We define *ecological constraint* as guaranteed levels of different biodiversity indicators. We sought to expand the use of a bioeconomic coviability approach to modeling and analysis of complex bioeconomic farming issues. We simultaneously accounted for spatial and multiscale dimensions and stochasticities. We also emphasized how PVA as it is applied in conservation biology in a focuses on extinction risks can be expanded to a bioeconomic viability or coviability approach. We aimed to shed light on public-policy issues and scenarios in terms of multifunctional agriculture and sustainable farming land-use and ecosystems.We determined to what extent a mix of taxes and subsidies on grasslands can promote a reconciliation of ecological and economic objectives.

Methods

Bioeconomic Model

Metropolitan France is split into 620 small agricultural regions (SAR). An SAR is part of a department (a major French administrative entity) that exhibits an agroecological homogeneity. This consistency from both the ecological and economic points of view makes the SAR scale well suited for our bioeconomic modeling. One model (described below) was built for each SAR.

To assess ecological performance of France, we focused on common bird populations (Ormerod & Watkinson 2000; Gregory et al. 2004). The French Bird Breeding Survey (FBBS) database (Jiguet et al. 2011) provided the information related to bird abundances across the entire country. Abundance values for each species were available for 2002–2008. Among the species monitored by this large-scale long-term survey, we selected 14 generalist species and 20 farmland specialist species that have been classified according to their habitat requirements at a European scale (European Bird Census Council 2007) (Supporting Information).

For agroeconomic data, we use the French agroeconomic classification Otea developed by the French Farm Accounting Data Network and the Observatory of Rural Development. This organization classifies agricultural land uses in 14 classes (Supporting Information). Each SAR is a specific combination of these 14 classes. The surfaces dedicated to each class and the associated gross margins are available for 2002–2008. We calibrated the budgetary constraint with the current French Common Agricultural Policy budget.

As depicted in Fig. 1, the bioeconomic model had 3 components articulated within a multiscale perspective as in Mouysset et al. (2011): the public policy at the large (national) scale interacts with the farming land uses and biodiversity dynamics at the local (SAR) scale.

Biodiversity Model

The biodiversity model dealt with a community of species. It was based on population dynamics with intraspecific competition that depended on habitat and farming land-use. A Beverton–Holt function captured intraspecific competition:

$$N_{s,r}(t+1) = N_{s,r}(t) \cdot \left(\frac{1 + R_{s,r}}{1 + \frac{N_{s,r}(t)}{M_{s,r}(t)}} + \varepsilon_{s,r}(t) \right), \qquad (1)$$

where $N_{s,r}(t)$ is abundance of species s in region r at year t and $R_{s,r}$ coefficient is intrinsic growth rate specific to a given species s in region r. The random variables $\varepsilon_{s,r}(t)$ capture the environmental stochasticity affecting the population dynamics, and these variables are drawn from Gaussian distributions calibrated with the historical growth rate compared with the estimated growth rate in the time series. Negative populations are considered extinct and consequently their abundances are forced to zero. The product $M_{s,r}(t) \times R_{s,r}$ is the carrying capacity of habitat r. The habitat parameter $M_{s,r}(t)$ captures the ability of habitat r to host the species s and is assumed to depend on the agricultural systems k as follows:

$$M_{s,r}(t) = \beta_{s,r} + \sum_{k} \alpha_{s,r,k}.A_{r,k}(t), \qquad (2)$$

where $A_{r,k}(t)$ is the share of the "utilized agricultural area" (UAA) of the small agricultural region r dedicated to the agricultural system k. Consequently, the $\alpha_{s,r,k}$ and $\beta_{s,r}$ coefficients, specific to each species, quantify how species s responds to agricultural land-use k in region r. The $\beta_{s,r}$ coefficient is the mean habitat coefficient for species s in region r and integrates other factors, such as the proportion of forest or urban areas. Parameters $\alpha_{s,r,k}$ and $\beta_{s,r}$ were calibrated with a least-squares method (Mouysset et al. 2013). The drivers of land-uses $A_{r,k}(t)$ are specified in the Economic Model section.

Economic Model

Although our bioeconomic model departs from optimality at the public-decision level to adopt a coviability viewpoint, as explained below, the model is still based on optimality at the microeconomic level through maximal expected utility of income of representative farmers. Each region is represented by a representative farmer or standard agent. The aggregation of individual farmers of a given SAR into a representative farmer is justified by the agroeconomic homogeneity of the SAR. Consequently, the farmers within an SAR face similar environments and constraints. The income per hectare in region r at year t, denoted by $\mathrm{Inc}_r(t)$, relies on the gross margin per unit of scale $\mathrm{gm}_{r,k}(t)$, current proportions of the UAA dedicated to the agricultural systems $A_{r,k}(t)$ and public incentives

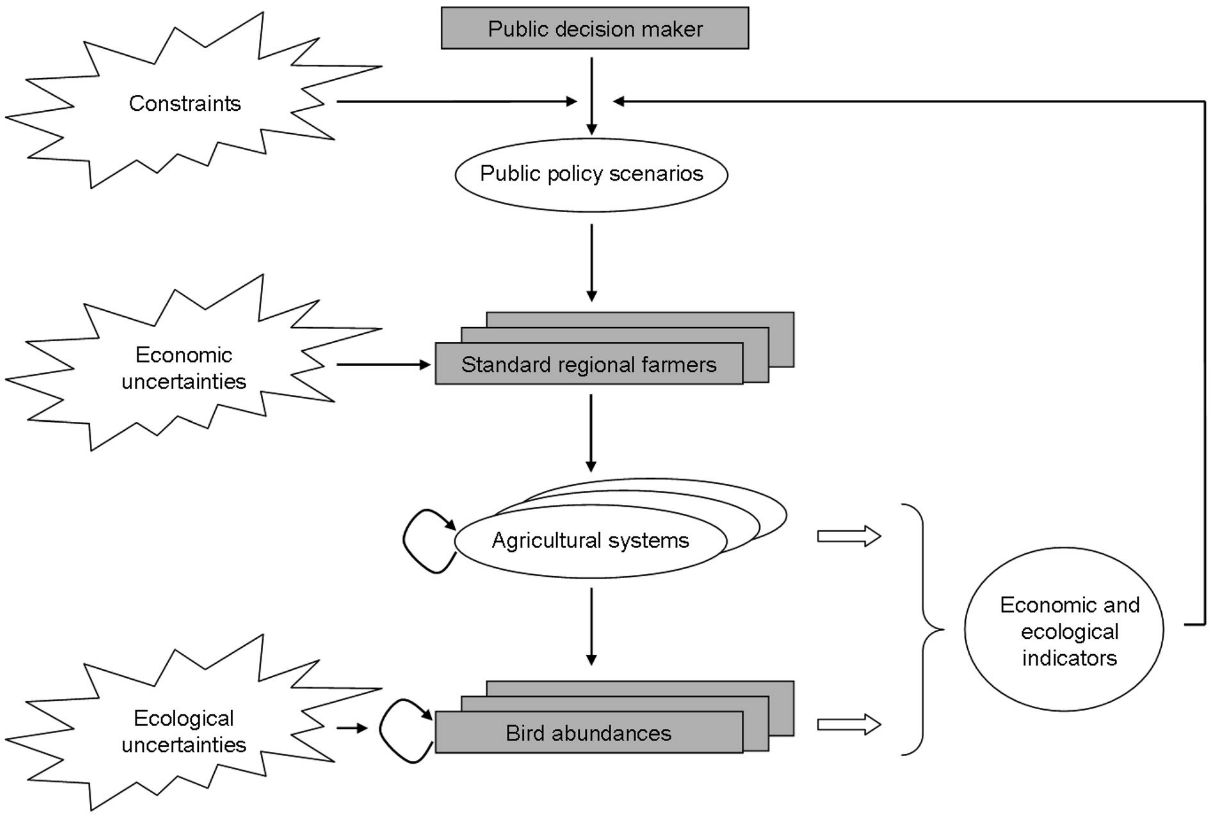

Figure 1. Structure of the bioeconomic model. The decision maker determines incentive scenarios (i.e., public policy scenarios) that affect farmers' decisions. The farmers choose their agricultural systems by maximizing their utility function under technical constraints. These choices affect habitat and bird communities in an uncertain context.

τ_k based on expected gross margins $\overline{\mathrm{gm}}_{r,k}$ as follows:

$$\mathrm{Inc}_r(t) = \sum_k A_{r,k}(t) \cdot (\mathrm{gm}_{r,k}(t) + \overline{\mathrm{gm}}_{r,k}\tau_k). \tag{3}$$

The public incentives are determinist and are computed as a percentage of expected gross margins: taxes with $\tau_k < 0$ and subsidies with $\tau_k > 0$. We assumed gross margins were stochastic and captured market, production and climate uncertainties. To characterize such randomness an independent and identically distributed Gaussian distribution parameterized with the mean and the covariance matrix of the historical data is chosen:

$$\mathrm{gm}_r(t) \to N(\overline{\mathrm{gm}}_r, \sum{}_r), \tag{4}$$

where expected gross margins $\overline{\mathrm{gm}}_{r,k}$ are the mean of the 7 historical years and the matrix $\sum_r$ of standard deviations is computed with the covariances $\sigma_{r,k,k'}$ between gross margins of agricultural systems k and k' in region r.

We assumed the land-use decisions of each representative farmer in region r relied on the maximization (under constraints) of the expected utility, $\mathrm{E}\,[U\,(\mathrm{Inc}_r\,(t))]$, derived from farming incomes per hectare. The selected utility function took an exponential form, $U\,(x) = 1 - e^{-ax}$, where parameter a is risk aversion level (also called the Arrow–Pratt index). Following Sargent (1987), we proved in the Gaussian context that

$$\mathrm{E}\,[U(\mathrm{Inc}_r(t))] = 1 - e^{-a\left(\mathrm{E}[\mathrm{Inc}_r(t)] - \frac{a}{2}\mathrm{Var}[\mathrm{Inc}_r(t)]\right)}. \tag{5}$$

In other words, maximizing the expected utility of incomes per hectare,

$$\max_{A_{r,1}(t);\cdots;A_{r,14}(t)} \mathrm{E}\,[U(\mathrm{Inc}_r(t))]\,, \tag{6}$$

is equivalent in terms of optimal land allocation to the maximization of a difference between the expected income $\mathrm{E}\,[\mathrm{Inc}_r\,(t)]$ and its risky part $\mathrm{Var}\,[\mathrm{Inc}_r\,(t)]$:

$$\max_{A_{r,1}(t);\ldots;A_{r,14}(t)} \mathrm{E}[\mathrm{Inc}_r(t)] - \frac{a}{2}\mathrm{Var}\,[\mathrm{Inc}_r(t)]\,, \tag{7}$$

where

$$\mathrm{E}[\mathrm{Inc}_r(t)] = \sum_k \overline{\mathrm{gm}}_{r,k}.A_{r,k}(t).(1+\tau_k) \ \text{ and} \tag{8}$$

$$\mathrm{Var}[\mathrm{Inc}_r(t)] = \sum_k \sum_{k'} \sigma_{r,k,k'}(t).A_{r,k}(t).A_{r,k'}(t) \tag{9}$$

For each year t, the regional standard agents chose their agricultural land uses, $A_{r,k}\,(t)$, in order to maximize their expected utility according to rigidity (Eq. 10) and surface constraints (Eq. 11). This approach follows the framework of maximization under constraints as in Polasky et al. (2005), Drechsler et al. (2007), and Mouysset et al. (2011). When maximizing the expected utility, the standard agent must comply with 2 constraints at every period:

$$|A_{r,k}(t) - A_{r,k}(t-1)| \leq \kappa . A_{r,k}(t-1) \text{ and } \quad (10)$$

$$\sum_k A_{r,k}(t) = 1 \quad (11)$$

The rigidity constraint (Eq. 10) restricts the area the farmer can modify at each period for each agricultural system k. The parameter κ captures change costs or inertia. The constraint (Eq. 11) ensures that the total UAA is kept fixed. The parameters a and κ are calibrated according to a least-squares method (Mouysset et al. 2013).

Thus, in this economic model, land uses $A_{r,k}(t)$ depend both on previous areas $A_{r,k}(t-1)$, the public policy incentives τ_k, expected gross margins $\overline{\text{gm}}_{r,k}$, covariance parameters $\sigma_{r,k,k'}$, the risk aversion level a, and the rigidity coefficient κ. The parameters $\overline{\text{gm}}_{r,k}$, $\sigma_{r,k,k'}$, κ, and a are exogenous, whereas the public incentives τ_k are endogenous and determined by a public decision maker according to a coviability approach explained in section 2.

Bioeconomic Indicators

We computed the indicators used to assess the ecological performances through the abundances $N_{s,r}(t)$ of each species. As suggested in Mouysset et al. (2012*b*), we analyzed the communities through a combination of the farmland bird index (FBI), community specialization index (CSI), and the community trophic index (CTI). The FBI, which measures the growth of the farmland specialist community, has been adopted by the European Community as the official environmental index, especially for analysis of structural changes in biodiversity (Balmford et al. 2003). In this aggregated index, the variation in abundances of each species is similarly taken into account independent of the abundance value. We first calculated a national population index for each species from the abundance values of all SAR r:

$$N_{s,\text{Nat}}(t) = \sum_r N_{s,r}(t). \quad (12)$$

Then we calculated the aggregated indicator FBI_{Nat}

$$\text{FBI}_{\text{Nat}}(t) = \prod_{s \in \text{Specialist}} \left(\frac{N_{s,\text{Nat}}(t)}{N_{s,\text{Nat}}(2008)} \right)^{1/20} \quad (13)$$

The CTI quantifies average trophic level of a community (Pauly et al. 1998). The CTI integrates the species trophic index (STI) of both the generalist species and the farmland specialist species (Supporting Information). The STI is built on the diets described in BWPi (2006) on the basis of the proportion of each species diet that is vegetable, invertebrate prey, and vertebrate prey (Mouysset et al. 2012*b*). The CTI classifies communities with mainly granivorous species (i.e., low trophic level) relative to communities with more insectivorous and carnivorous species (i.e., high trophic level) (Mouysset et al. 2012*b*). We computed it as the arithmetic mean of the exponential of the species trophic level weighted by abundances of each species in the community

$$N_{\text{tot},r}(t) = \sum_s N_{s,r}(t) \text{ and } \quad (14)$$

$$\text{CTI}_r(t) = \sum_s \frac{N_{s,r}(t)}{N_{\text{tot},r}(t)} . \exp(\text{STI}_s) \quad (15)$$

We used an exponential function to better contrast communities with or without bird individuals of the higher trophic levels. The CTI_{Nat} is the arithmetic mean of the 620 regional CTI_r

$$\text{CTI}_{\text{Nat}}(t) = \frac{1}{620} . \sum_r \text{CTI}_r(t) \quad (16)$$

Finally, the CSI quantifies the response of the composition of local bird communities to agricultural pressures (Barnagaud et al. 2011). Habitat specialization species index (SSI) has been computed for each species, based on the coefficient of variation of the abundance of a species across 18 habitat categories (Julliard et al. 2006). The SSI values for all the species we considered here are in Mouysset et al. (2012*b*). This index measures the average degree of habitat specialization among the individuals of the community. It discriminates the ordinary community of generalist species, which are more resilient to perturbation, from the specialized communities with more specialist species, which are especially sensitive to global change (Julliard et al. 2006). For each square, we calculated the local CSI_r as the arithmetic mean of the species specialization index weighted by the abundances (Eq. 14) and

$$\text{CSI}_r(t) = \sum_s \frac{N_{s,r}(t)}{N_{\text{tot},r}(t)} . \text{SSI}_s \quad (17)$$

We calculated the national CSI_{Nat} as the arithmetic mean of the 620 regional CSI_r:

$$\text{CSI}_{\text{Nat}}(t) = \frac{1}{620} . \sum_r \text{CSI}_r(t) \quad (18)$$

We measured the economic performance of farmers by national income:

$$\overline{\text{Inc}}_{\text{Nat}}(t) = \frac{1}{S_{\text{Nat}}} \sum_r S_r . \text{Inc}_r(t), \quad (19)$$

where $S_{\mathrm{Nat}} = \sum_r S_r$ is the total agricultural surface of SAR over France and S_r is the agricultural area of the small agricultural region r.

Hereafter, the public budget played a major role in the analysis of viability of public policies. This budget, Budg(t), was computed according to the incentives as follows:

$$\mathrm{Budg}(t) = \sum_r \sum_k S_r.\overline{\mathrm{gm}}_{r,k}.A_{r,k}(t).\tau_k \tag{20}$$

Coviability Scenarios

In the coviability approach, we considered both biodiversity and economic viability objectives through a large set of constraints to be satisfied. The constraints had to be satisfied in the probabilistic sense as in Doyen and De Lara (2010) and Doyen et al. (2012). Given a confidence rate, the viable kernel makes it possible to identify different public policies and scenarios with admissible agroecological risk. We now describe the different constraints taken into account hereafter. We compared the constraint scenarios with the Statu Quo (SQ) scenario, which corresponds to the performances obtained if the land uses were fixed to the 2008 levels:

$$A_{r,k}^{\mathrm{SQ}}(t) = A_{r,k}(2008), \quad t = 2009, \ldots, T \tag{21}$$

Ecological Constraints

We defined ecological constraints as guaranteed levels of biodiversity for different biodiversity indices: FBI, CSI, and CTI. The viability thresholds for the constraints were based on the performances of these indices ($\mathrm{FBI}^{\mathrm{SQ}}(t)$, $\mathrm{CTI}^{\mathrm{SQ}}(t)$, $\mathrm{CSI}^{\mathrm{SQ}}(t)$) obtained with the SQ scenario as defined by Eq. 21. It is thus required that

$$\mathrm{FBI}(t) \geq \lambda \cdot \mathrm{FBI}^{\mathrm{SQ}}(t) \tag{22}$$

$$\mathrm{CTI}(t) \geq \lambda \cdot \mathrm{CTI}^{\mathrm{SQ}}(t) \tag{23}$$

$$\mathrm{CSI}(t) \geq \lambda \cdot \mathrm{CSI}^{\mathrm{SQ}}(t) \tag{24}$$

where λ is the strength of the constraint. We tested 3 levels of strength: $\lambda = 90\%$, $\lambda = 93\%$, and $\lambda = 95\%$.

Economic Constraints

For economic constraints, determination of the economic viability of public policies requires that the income per hectare Inc(t) derived from farming activities are not worse than the current or SQ level, $\mathrm{Inc}^{\mathrm{SQ}}(t)$, derived from (Eq. 21)

$$\mathrm{Inc}(t) \geq \lambda \cdot \mathrm{Inc}^{\mathrm{SQ}}(t) \tag{25}$$

Public-policy scenarios were also constrained to comply with a budgetary rule (Eq. 26)

$$\mathrm{Budg}(t) \leq \mathrm{Budg}(2008) \tag{26}$$

where Budg(t) stands for the budget dedicated to the farming policy. The budget constraint means that, for each year, the decision maker has a budgetary envelope. This budget can be allocated among the different land uses according to the objectives of the agency. Because of this annual envelope, it is possible to have many subsidies simultaneously. In other words, a subsidy on one side does not need to be compensated by a tax on the other. Of course, if the decision maker wants to strongly increase the subsidy on one side (more than the envelope), a tax will be required on the other side to avoid violating the budgetary constraint. This situation is consistent with reality, where the European states receive a budgetary envelope from the EU and from their own government. The national budget for agricultural policies does not derive only from farming taxes. In our simulation, we used the French budget, Budg (2008) (which is the final year of our time series), as reference for the budgetary envelope.

Viable Incentives

We based the public policies in this study on incentives τ (subsidies and taxes) allocated to the different agricultural systems k. Bioeconomic performances in response to these scenarios were computed from 2009 to 2050 ($T = 2050$) according to the ecological and economic objectives described above.

For computational reasons, the public-decision variables were restricted to 2 incentives: cereal incentive τ_{crop} is dedicated to arable lands (Supporting Information) and the grassland incentive τ_{grass} is applied to nonintensive grassland systems (Supporting Information).

We dealt with uncertainty in a probabilistic sense. We therefore performed a stochastic coviability analysis (CVA). For this, we considered a probability P on scenarios $\omega(.) \in \Omega$ associated with stochastic variables $\mathrm{gm}_{r,k}(t)$ and $\varepsilon_{r,k}(t)$. For each public-decision scenario τ, we compute the probability of satisfying the different bioeconomic constraints over time:"

$$\mathrm{CVA}(\tau) = P\Big(\text{Constraints}\,(22), (23), \big(24\big), (25) \text{ and } \big(26\big), \text{holds for } t = 2009, \ldots, 2050\Big). \tag{27}$$

Given a confidence rate $\beta \in [0, 1]$, we aimed to identify the controls τ_{crop} and τ_{grass} that satisfy the following condition:

$$CVA(\tau) \geq \beta. \quad (28)$$

Given a level of risk $1 - \beta$, we sought to identify viable incentives $\tau = (\tau_{crop}, \tau_{grass})$ that satisfied viability condition (Eq. 28). Of particular interest were the incentives that maximized the viability probabilities, that is $\max_\tau CVA(\tau)$. Given a level of risk $1 - \beta$, we defined the viable decision kernel τ^{β}_{VIAB} as

$$\tau^{\beta}_{VIAB} = \{\tau,\ CVA(\tau) \geq \beta\}. \quad (29)$$

Given the stochastic framework, the outcomes of every incentive scenario, $\tau = (\tau_{crop}, \tau_{grass})$, were generated 100 times to approximate its viability probability $CVA(\tau)$. We assumed Gaussian independent and identically distributed random variables gm(t) and introduced ε in Eq. 3 and Eq. 1, respectively.

Results

Public Policies and Bioeconomic Constraints

We found a viable set τ_{VIAB} of public policies that balanced the economic and ecological objectives with limited risk (Fig. 2). The set (black in Fig. 2) satisfies the constraints with a high confidence rate $\beta = 100\%$. This viable kernel τ_{VIAB} relied on subsidies for nonintensive grasslands $(\tau_{grass} \geq 0)$ and taxes for crops $(\tau_{crop} \leq 0)$. However, the incentives could vary significantly within this kernel ($0.3 \leq \tau_{grass} \leq 0.6$ and $-0.2 \leq \tau_{crop} \leq -0.7$ in the case $\lambda = 93\%$) and still maintain the same bioeconomic risk.

Economic Sensitivity

The budgetary constraint Eq. 26 offers a large set of possibilities of public policies to which other constraints can be added (Fig. 3). Because of the existence of the annual envelope Budg (2008), which can be distributed in each year, it was possible to combine simultaneously subsidies on both grasslands and croplands. However, if the subsidies were too high, the required budget exceeded the annual envelope and the budgetary constraint was violated. The budgetary constraint offers a large set of possibilities of public policies to which other constraints can be added.

With the economic constraint, viable policies exist in the upper triangle beyond a decreasing line between crop and grassland incentives (Fig. 4). Typically, to satisfy the income constraint, it was possible to use subsidies on both grasslands and croplands. It was also possible to reduce 1 of the 2 subsidies and transform it to taxes, but the other incentive had to be increased to compensate

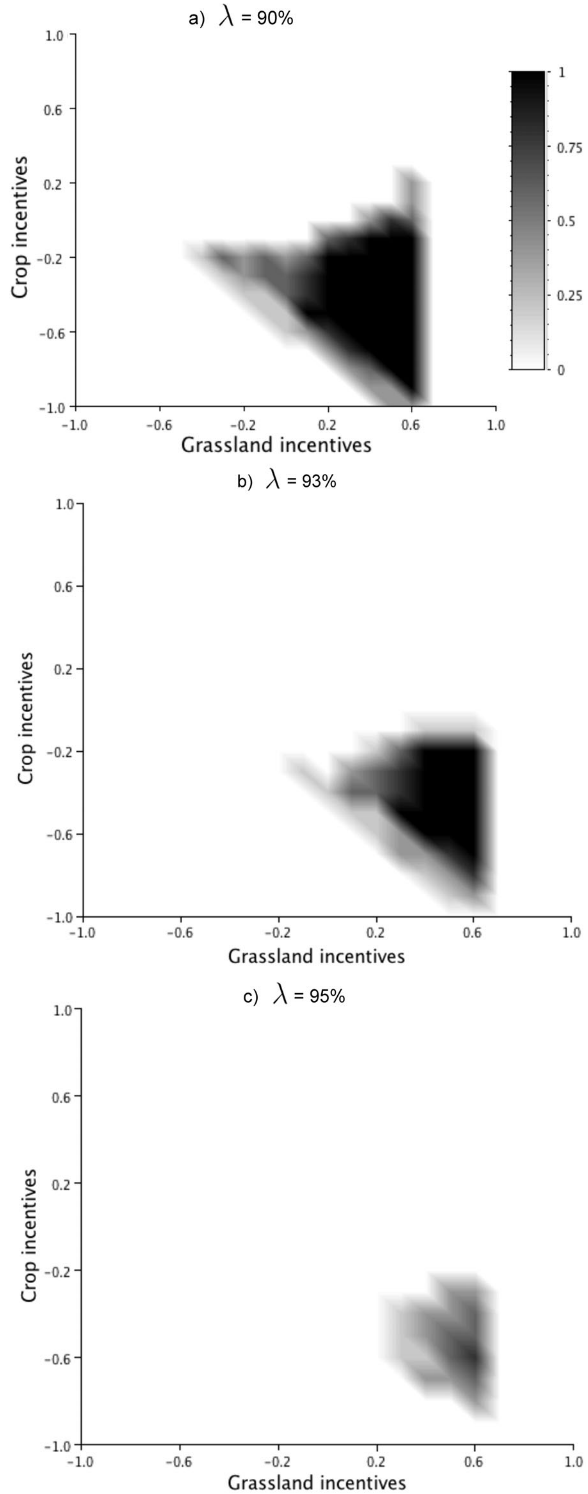

Figure 2. Coviability probabilities $CVA(\tau)$ *that the grassland- and crop-incentive scenarios satisfy the set of constraints (budget, income, farmland bird index, community trophic index, community specialization index). Lambda ((a) 90%, (b) 93% and (c) 95%) represent the strength of the constraints (Eqs. 22, 23, 24, 25). The degree of shading represents probability from 0 (white) to 1 (black).*

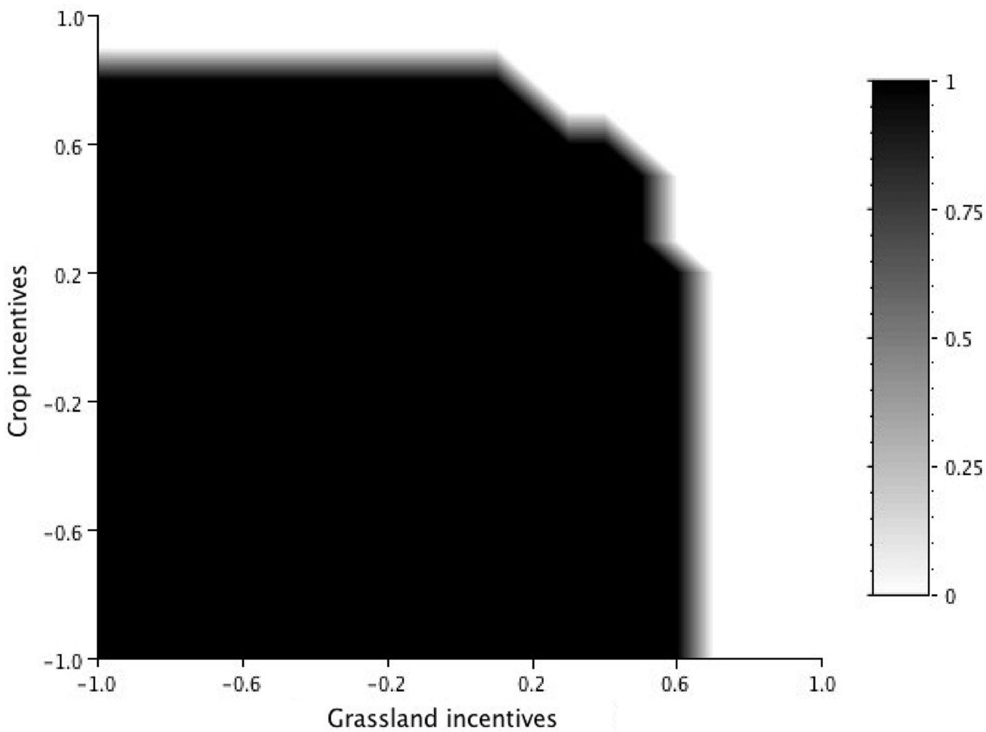

Figure 3. Probabilities that the grassland- and crop-incentive scenarios satisfy budgetary constraint (Eq. 26). The degree of shading represents probability from 0 (white) to 1 (black).

the economic loss. When the economic objective was more demanding (i.e., λ increased in Eq. 25), the trade-off moved upward, and the size of the feasible incentive was reduced: the reduction of one incentive required a larger increase in the other incentive.

Two of the 3 edges of the viable kernels in Fig. 2 arose from the economic constraints: the vertical edge on the left resulted from the budgetary constraint, whereas the diagonal edge on the right resulted from the income requirement (Figs. 2–4).

Ecological Sensitivity

The FBI constraint was the most restrictive (Fig. 5). For the same strength of constraint λ, the set of acceptable public policies obtained with the FBI constraint was smaller than the one obtained under the CTI and CSI constraints. Furthermore, for these levels of constraint, the constraints on the CTI and the CSI were not binding: the entire set of strategies complied with these constraints over time.

With the FBI constraint (Eq. 22), the set of feasible public policies exits in the lower right square between the 2 incentives (τ_{grass} and τ_{crop}). To satisfy the FBI constraint with a high confident rate ($\beta = 100\%$, dark shading in Figs. 5a–c), the public policy had to combine subsidies on grasslands and taxes on croplands. When the subsidy on grasslands was decreased, this action had to be compensated for by a larger tax on croplands. Alternatively, when the subsidy on grasslands increased, the pressure on croplands decreased, and it was possible to combine the increased subsidy on grasslands with a smaller tax on croplands by staying within the kernel. When the FBI constraint was more stringent (i.e., λ is increased in Eq. 22), the positive trade-off is moved downward. In other words, to stay within the kernel with a high confidence rate, the pressure on taxes on croplands has to increase if the grassland subsidies decrease.

The horizontal boundary on the top of the viable kernels in Fig. 2 resulted from the ecological constraint related to FBI requirements (Fig. 5).

Trajectories and Land Uses

When the constraint threshold was set at $\lambda = 93\%$, the scenario that combined taxes $\tau_{\text{crop}} = -0.2$ on cropland and subsidies $\tau_{\text{grass}} = 0.6$ was an example of a viable public policy (Fig. 6). Viable scenarios are associated with a substitution of cropland by nonintensive grasslands (Fig. 7).

Discussion

Coviability Approach to Address Sustainability

The use of bioeconomic models and viability assessments integrating ecological and socioeconomic processes and

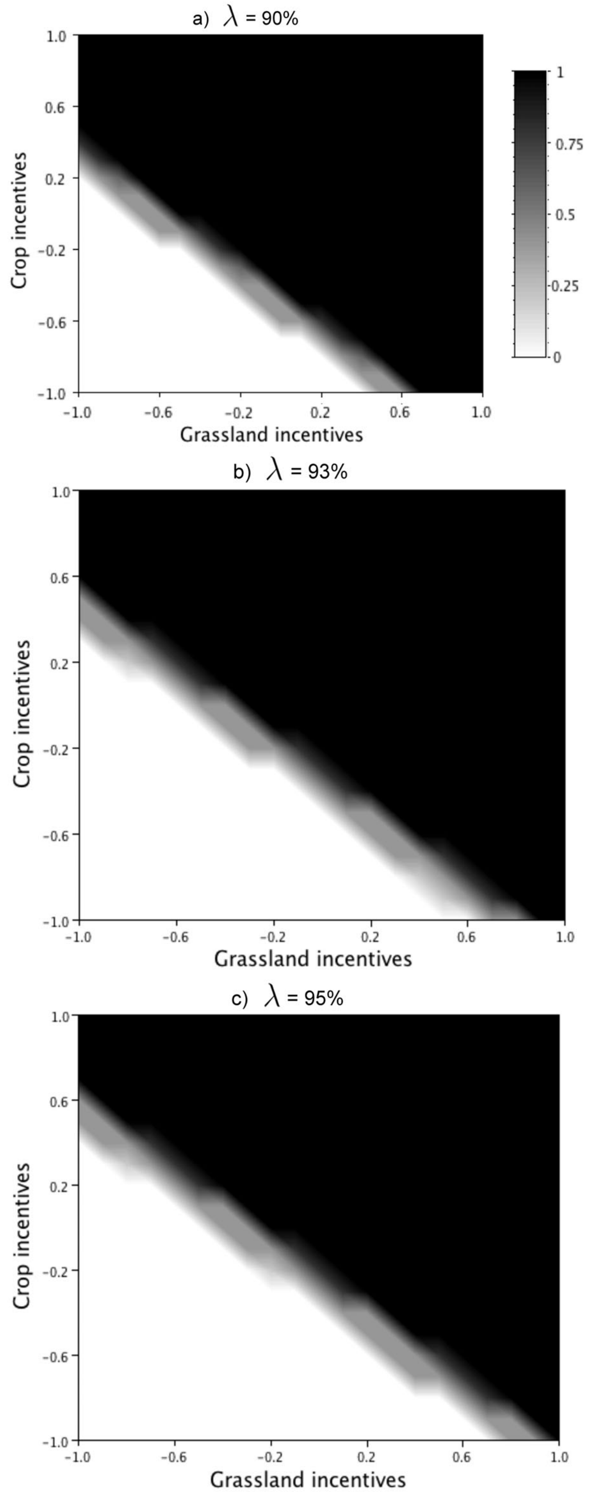

Figure 4. Probabilities that the grassland- and crop-incentive scenarios satisfy economic constraint (Eq. 25). Sensitivity analysis is with respect to the strength of the constraint. Lambda ((a) 90%, (b) 93% and (c) 95%) represent the strength of the constraint (Eq. 25). The degree of shading represents probability from 0 (white) to 1 (black).

goals was highlighted by Béné et al. (2001), Doyen et al. (2012), and Péreau et al. (2012). Our results confirm that this viability method is a convenient tool to reconcile apparently contradictory objectives. Indeed, many studies based on optimal control approaches have identified a Pareto-optimum frontier between the ecological and economic performance of agriculture (Polasky et al. 2005; Barraquand & Martinet 2011). In other words, there is no unique scenario that maximizes ecological and economic criteria simultaneously. Our approach offers a more flexible sustainability framework that allows one to balance different goals. In the stochastic context discussed in Baumgärtner and Quaas (2009), Doyen et al. (2007, 2012), by examining both ecological and socioeconomic risks, this bioeconomic viability or coviability framework extends PVA used in conservation biology (Morris & Doak 2002).

Beyond the analysis of our French case study, our results support an integrated and multicriteria approach that involves many scientific disciplines in broad collaborative efforts. A wide range of stakeholders are involved in agroecological and farming land-use issues. Each of these groups has an interest in particular outcomes, and some outcomes considered desirable by one stakeholder may be undesirable to another group. The consideration of the multidimensional nature of farming is helpful for sustainable management of terrestrial resources and biodiversity and brings together economic, environmental, and social viewpoints. Our study is in direct line with these considerations.

Moreover, by focusing on sustainability and viability, our model resulted in management strategies and scenarios that satisfied different constraints over time. Thus, the model accounts for intergenerational equity and allows for conciliation between the present and the future. By identifying current public-policy decisions that avoid future crises without penalizing the current generation, the viability approach is consistent with the definition of sustainability especially through its links with the maximum (or Rawlsian) approach (i.e., approach focused on the maximization of the poorest generation) as emphasized in Doyen and Martinet (2012).

By reconciling apparently antagonistic objectives and offering a multicriteria and intertemporal equity framework, the coviability strategy turns out to be a promising approach to address sustainability. This strongly argues in favor of the use of the coviability framework by decision makers to analyze public-policy scenarios as a complement to the more usual cost-effectiveness or cost-benefit approaches.

Moreover, through this work we have expanded the application of the approach to complex bioeconomic, land-use, and agroecological contexts. In particular, the incorporation of both spatial or multiscale dimensions is new. The mix of ecological and economic stochasticities

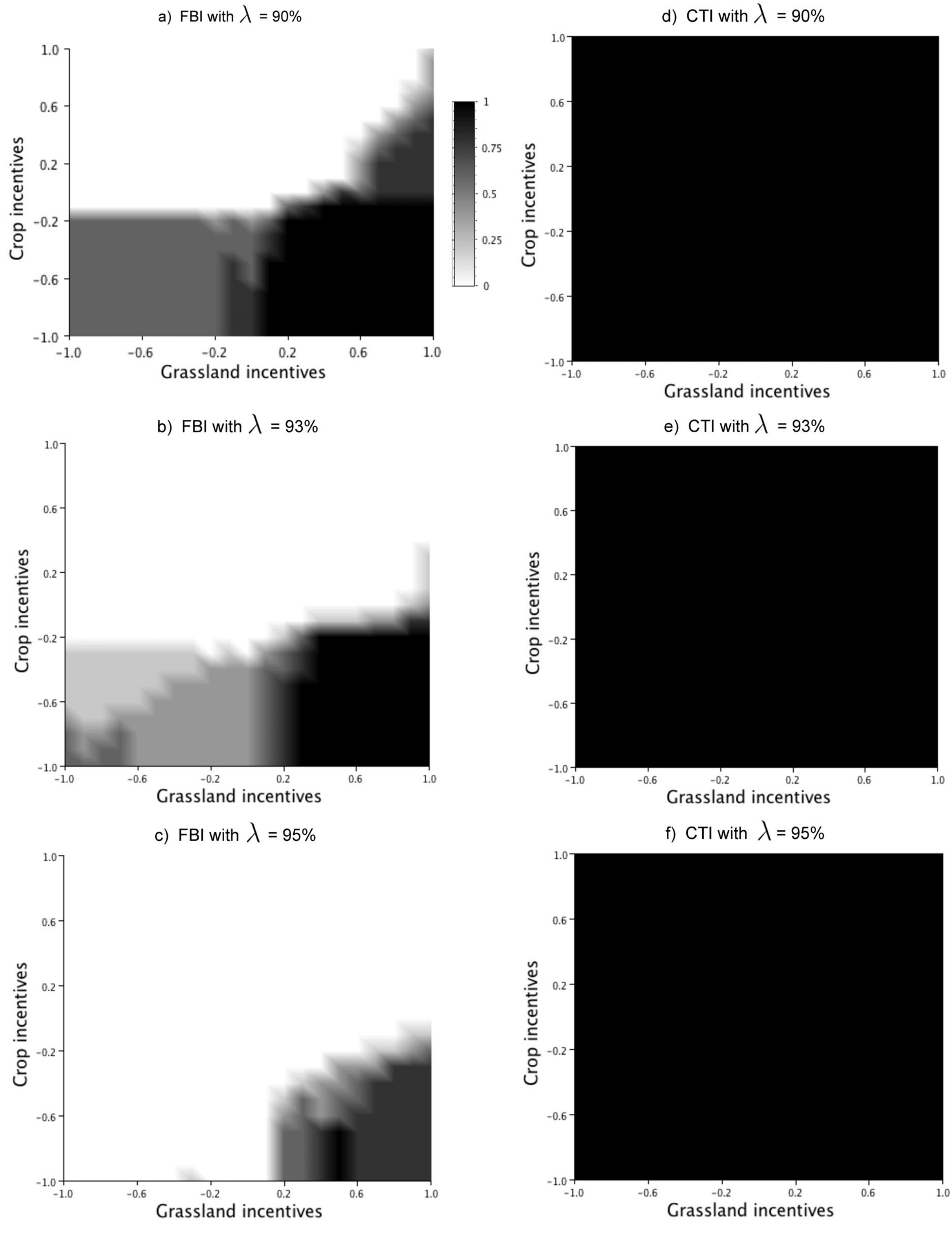

Figure 5. Probabilities that the grassland- and crop-incentive scenarios satisfy ecological constraints : (a)–(c) farmland bird index (FBI) (Eq. 22), (d)–(f) community trophic index (CTI) (Eq. 23), and (g)–(i) community specialization index (CSI) (Eq. 24). Sensitivity analysis is with respect to the strength of the constraint with $\lambda = 90\%, 93\%, 95\%$, where λ is the strength of the constraints (Eqs. 22, 23, 24). The degree of shading represents probability from 0 (white) to 1 (black).

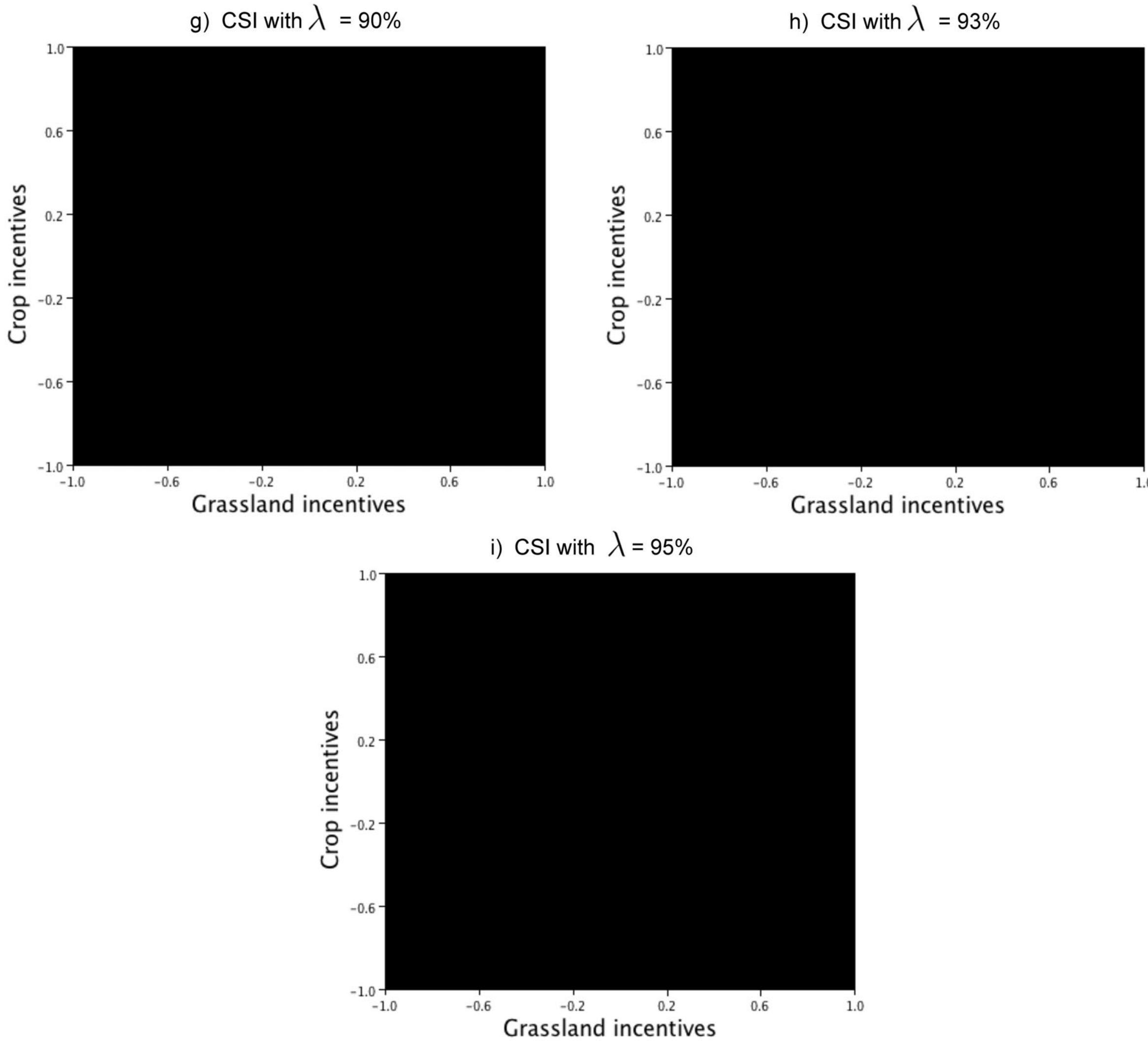

Figure 5. Continued.

also constitutes a new stage for the development of the approach.

Decision Support for Farming Land-Use and Farmland Biodiversity

We developed a dynamic bioeconomic model to represent and agroecosystem. Our model combines multispecies and multiscale considerations. The coviability analysis identified public policies for multifunctional and sustainable agriculture.

We found that viable policies were based on a combination of taxes on crops and subsidies on extensive and semiextensive grasslands. The positive effect of the development of grasslands to achieve biodiversity goals has been shown (Potter & Goodwin 1998; Laiolo 2005). Here, we argue this point within a broad context: according to a multicriteria and bioeconomic perspective that integrates risk management and accounts for intergenerational equity.

According to our economic data set, which implicitly integrated current public policy, the combination of crop taxes and grassland subsidies can be interpreted as a reduction of the current subsidies on croplands in the first pillar of the Common Agricultural Policy and a development of the second pillar subsidizing extensive grasslands. This highlights the importance of the 2 pillars in achieving sustainable agricultural public policies. In other words, it is not sufficient to increase the second pillar without changing the first. From an economic viewpoint, this result is not surprising. The underlying principle is the management of externalities: negative externalities (e.g., crops, which have on average a negative effect on biodiversity) are taxed, whereas positive externalities (e.g., grasslands which have on average a positive effect on biodiversity) are supported and subsidized.

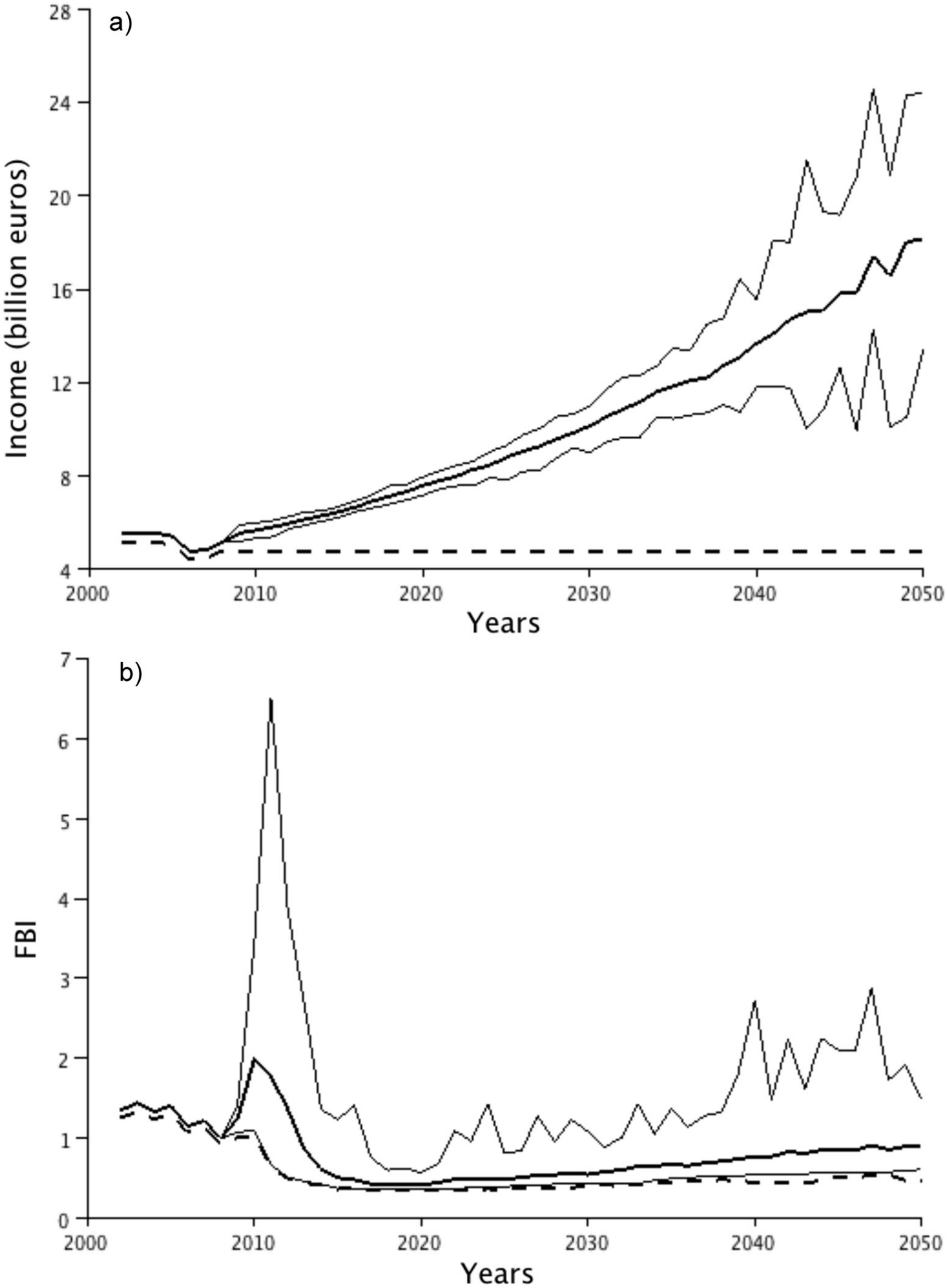

Figure 6. (a) Economic (income) and (b) ecological (related to the farmland bird index [FBI]) performances of a viable scenario of crop and grassland incentives, $\tau = (\tau_{\text{grass}}, \tau_{\text{crop}}) = (0.6, -0.2)$ *., built with a strength of constraints* $\lambda = 93\%$ *(mean, thick solid lines; minimum and maximum, thin solid lines; constraint, dashed lines).*

The grassland incentives we considered are in direct line with current public policies for multifunctional agriculture and land-use through AES. Typical among the numerous AES implemented since 2005 is the direct subsidy of extensive grasslands. Furthermore, subsidies do not generally raise substantial concerns in terms of acceptability among farmers because they constitute a financial gain for them. In contrast, there are questions over acceptability of taxes on crops, particularly among arable-land farmers. The satisfaction of the budgetary constraint over time under the viable policy yielded some insights into this acceptability issue. The budgetary constraint was only binding on the left boundary of the kernel (Fig. 2). In other words, some viable strategies (strategies inside the kernel) induced some budgetary benefit as detailed in Mouysset et al. (2012*a*). This suggests that some

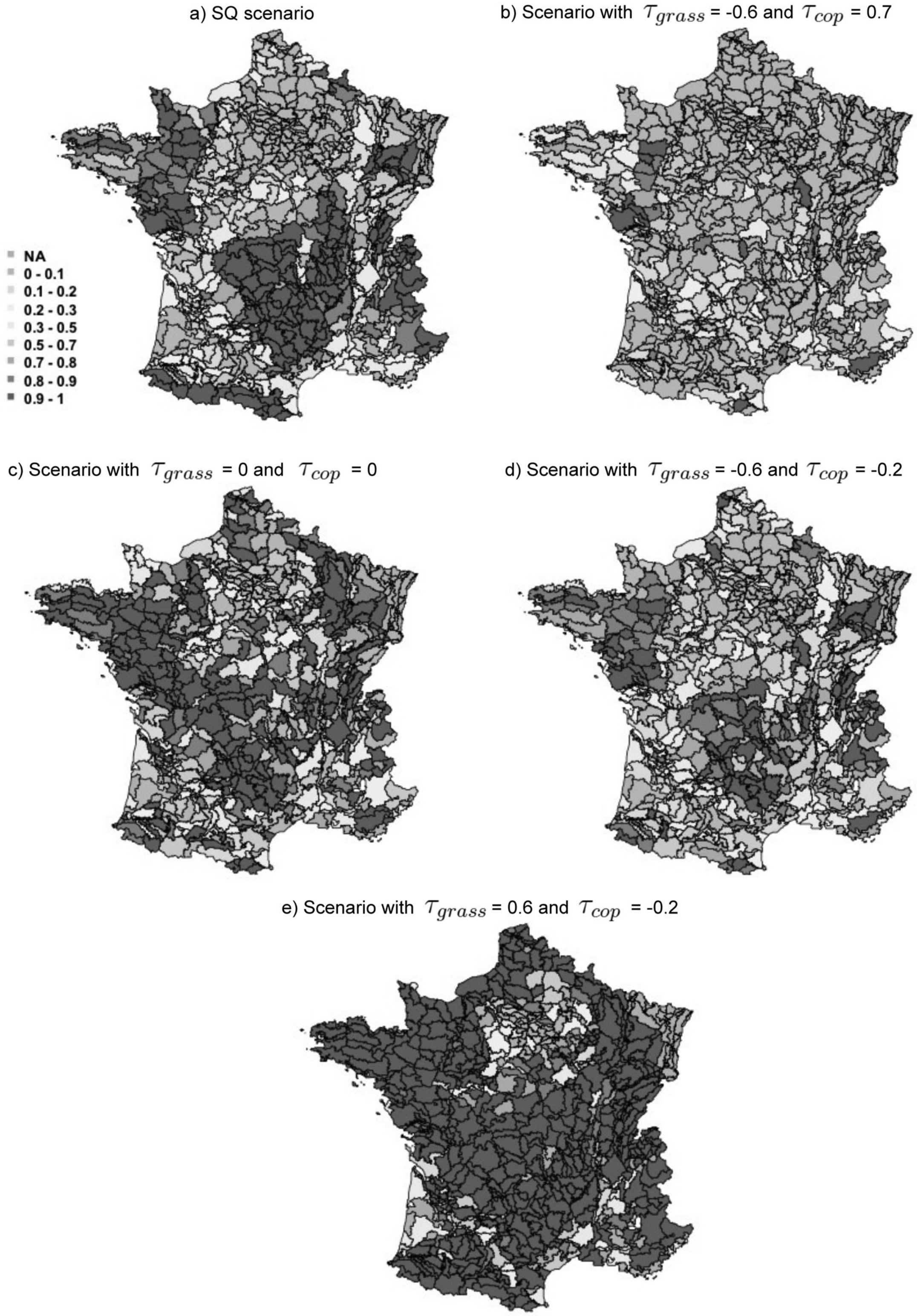

Figure 7. Ratio of grasslands to the sum of crop and grassland areas with the (a) statu quo scenario and (b–e) 4 public-policy scenarios in 2050. Fig. 7d corresponds to the scenario in Fig. 6.

redistribution could occur from the budget gain to those farmers incurring private costs and losses due to taxes on crops. Such a financial reallocation could promote the acceptability and governance of such strategies. Moreover, the size of the kernel of viable strategies offers additional flexibility to integrate other constraints, such as social objectives that could also be fruitful in terms of acceptability and governance.

As suggested by Mouysset et al. (2012*b*), we integrated the 3 indicators FBI, CSI, and CTI as ecological criteria of biodiversity. The sensitivity analysis showed that the FBI was the most sensitive and the most restrictive criteria. In others words, by sustaining the FBI, the 3 ecological constraints were satisfied. This result validates the choice of this indicator by the European Union as an indicator of structural biodiversity changes in response to agricultural evolution (Balmford et al. 2003), even if this is not the most relevant in functional terms.

New Directions and Method Improvements

First, other policies, incentives, and tools can be integrated to reinforce the credibility of the public-policy scenario we examined. For example, the classical AES as currently implemented in France could be modeled in more detail. Second, refinements might concern modeling bird population dynamics by integrating species dispersal and interactions and detailing the functions of the birds in the agroecosystem. In particular, the spatial scale we used (small agricultural regions) provided agroecological consistency and may be appropriate for modeling public policies and agricultural practices. However, it might not be the best scale with which to model bird population dynamics. A landscape scale seems relevant for analysis of the biodiversity-oriented agricultural public policy (Batary et al. 2011). Third, relevant new indicators could be added to the constraints involved in our method. For instance, social requirements such as inter-regional equity or productivity constraints might be taken into account.

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Supporting Information

The list of the 10 farmland and the 14 generalist (Appendix S1) and of the 14 farming land uses (Appendix S2) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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