



**HAL**  
open science

## From population viability analysis to co-viability of farmland biodiversity and agriculture

Lauriane Mouysset, Luc Doyen, Frédéric Jiguet

► **To cite this version:**

Lauriane Mouysset, Luc Doyen, Frédéric Jiguet. From population viability analysis to co-viability of farmland biodiversity and agriculture. *Conservation Biology*, 2014, 28 (1), pp.187-201. 10.1111/cobi.12184 . hal-01198099

**HAL Id: hal-01198099**

**<https://hal.science/hal-01198099v1>**

Submitted on 27 May 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Co-viability of farmland biodiversity and agriculture

L. Mouysset<sup>a,b</sup>, L. Doyen<sup>a</sup>, F. Jiguet<sup>a</sup>

<sup>a</sup>*CNRS, CERSP, UMR 7204 CNRS-MNHN-UPMC, 55 rue Buffon, 75005 Paris Cedex, France.*

<sup>b</sup>*INRA, SADAPT, UMR 1048 INRA-AgroParisTech, 16 rue Claude Bernard, 75005 Paris Cedex, France.*

---

## Abstract

Significant declines of farmland biodiversity have been reported in Europe since several decades. Agricultural changes have been identified as a main driver of this erosion. Although different agri-environmental schemes have been implemented, their positive role on biodiversity remain controversial. This questions the way to reconcile farming production and biodiversity conservation in order to operationalize a sustainable and multifunctional agriculture. To deal with such issues, the present paper proposes a bio-economic model and an analysis based on a co-viability perspective. The model couples stochastic dynamics of both biodiversity and farming land-uses selected at micro level with public policies at macro level based on financial incentives (taxes or subsidies) for land-uses. The co-viability approach allows to evaluate bio-economic risks for these public incentives through the probability to satisfy a mix of biodiversity and economic constraints throughout time. The model is calibrated and applied to metropolitan France at SAR (small agricultural regions) scale using a community of 34 common birds. The viable kernel allows to identify different public policies and scenarios with tolerable agro-ecological risk. It suggests how some combinations of taxes on cereals and subsidies on grasslands could be relevant. Moreover, the flexibility and multi-criteria viewpoint underlying the approach can be fruitful for decision makers in the perspective of adaptive management.

*Keywords:* Bio-economics, modeling, Viability, Bird, Farming, Land-use.

---

## 1. Introduction

Significant declines of biodiversity have been reported worldwide for several decades (Butchart *et al.* 2010). This is especially documented in Europe for mammals in Flowerdew & Kirkwood (1997), for arthropods and plants in Sotherton & Self (2000) or for birds in Donald *et al.* (2001). Such erosion is mainly due to a combination of habitat loss and degradation of habitat quality altering the nesting success and/or survival rates (Benton *et al.* 2002). Modern agriculture and associated intensification of practices have been identified as major drivers of this erosion in farmland biodiversity (Krebs *et al.* 1999, Jiguet 2010). In this context, the need to reconcile in a sustainable way economic and conservation objectives 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 & Gill (2005), Mouysset *et al.* (2011). The public policies can potentially modify the farmer's choices in terms of land-uses and practices and thus impact both the habitat and the dynamics of biodiversity (Doherty *et al.* 1999, Holzkamper & Seppelt 2007, Rashford *et al.* 2008). In this perspective, many public policies including agri-environmental schemes have been proposed by decision makers. However, fifteen years after the initial implementation of such instruments at a large scale, their ability to enhance biodiversity remains controversial (Vickery *et al.* 2004, Kleijn *et al.* 2006, Butler *et al.* 2009). Thus the conservation and the sustainable management of farmland biodiversity still constitute difficult scientific challenges.

To address such agro-ecological issues, the use of bio-economic models can be fruitful. Different bio-economic modeling frameworks have been proposed in the literature. Many rely on the optimal-control theory (Polasky *et al.* 2005, Drechsler *et al.* 2007, Holzkamper & Seppelt 2007). In particular, cost-benefit methods require quantification of biodiversity in monetary terms (Drechsler 2001, Rashford *et al.* 2008). Although pricing techniques such as contingent valuation are available, their suitability for biodiversity is disputed (Diamond & Hausman 1994). In this context, cost-effectiveness is an interesting alternative to avoid monetary evaluation of environmental goods (Gatto & De Leo 2000). Approaches such as ecological economics suggest studying environmental and economic performances simultaneously, stressing the relevance of multi-criteria approaches (Drechsler *et al.* 2007, Mouysset *et al.* 2011). However the choice of metrics for evaluating biodiversity is not straightforward and indicators used to assess biodiversity and environmental services are diverse (van Wenum *et al.* 2004, Havlik *et al.* 2005, Polasky *et al.* 2005, Mouysset *et al.* 2012a). Moreover, numerous models emphasize spatial dimensions in dealing with agro-ecological issues. Such spatially explicit models aim at assessing consequences of different land use patterns for various environmental and economic criteria (Irwin & Geoghegan 2001, Swihart *et al.* 2003, Polasky *et al.* 2005, Groot *et al.* 2007). Nevertheless, most of these models are static, restricting the potential ecological processes accounted for. In the same vein, most of these models are deterministic and do not take into account the various uncertainties involved in the ecological and economic processes at play.

The bio-economic model proposed in this article is in direct line with these considerations. First, adopting a spatio-temporal and multi-scale viewpoint, it articulates biodiversity community dynamics with farming land-uses selected by heterogeneous agents at micro (landscape) level and macro (typically national) financial incentives associated with land-uses. Moreover the model accounts for bio-economic uncertainties through stochasticity both on community dynamics and gross margins. Second a viability or co-viability approach is applied to the bio-economic model to identify public policies promoting a multifunctional and sustainable agriculture.

The viability (or viable control) approach aims at identifying desirable combinations of states and associated controls that ensure the 'good health', safety or effectiveness of the system (Aubin 1991, Béné *et al.* 2001). This approach focuses on feasible paths within a set of desirable objectives or constraints. This framework has been applied to renewable resources management in Béné *et al.* (2001), Martinet *et al.* (2007), De Lara *et al.* (2007), Péreau *et al.* (2012), as well as to broader (eco)-system dynamics (Cury *et al.* 2005, Doyen *et al.* 2007; 2012). Specific focus on agro-ecological issues can be found in Tichit *et al.* (2007), Sabatier *et al.* (2012). In bio-economic contexts, viability does not aim at identifying optimal or steady state paths for the co-dynamics of resources and exploitation but, instead, provides acceptable trajectories and controls satisfying both socio-economic and ecological constraints. In this respect, it is a multi-criteria approach (Baumgärtner & Quaas 2009). Moreover, by identifying the conditions that allow desirable objectives to be fulfilled over time, considering both present and future states of a system, the viability approach conveys information on sustainability. In particular, the approach is also closely related to the maximin, or Rawlsian, approach with respect to intergenerational equity (Martinet & Doyen 2007). Furthermore, Tichit *et al.* (2007), De Lara *et al.* (2007), De Lara & Doyen (2008), Doyen *et al.* (2012) shows how the so-called Population Viability Analysis (PVA) developed in conservation biology addresses issues comparable to those of the viability approach. Cury *et al.* (2005), Doyen *et al.* (2012) illustrate how the viability approach can potentially be useful to integrate ecosystem considerations into management.

This viability or co-viability approach is here applied to a complex agro-ecological model in order to assess the possible reconciliation between conservation goals and economic requirements. The co-viability approach allows to evaluate the bio-economic risks for the public incentives through the probability to satisfy a set of ecological and economic constraints throughout time. By ecological constraint is meant guaranteed levels for different biodiversity indicators. The method is applied to the metropolitan France case study. The calibration relies on French time series of 34 birds abundance and 14 farming agricultural systems over years 2002-2009 and 620 small agricultural regions in metropolitan France. Three indicators which has been identified in Mouysset *et al.* (2012a) as relevant to characterize the state of bird community in response of agricultural public policies capture the biodiversity scores: the Farmland Bird Index which has been adopted by the European Union (Balmford *et al.* 2003, Gregory *et al.* 2004), the Community Specialization Index which evaluates the dependence of

the community of a habitat (Barnagaud *et al.* 2011) and the Community Trophic Index based on the species diets (Pauly *et al.* 1998).

## 2. The bio-economic modeling

### 2.1. Context and data

Metropolitan France is split into 620 Small Agricultural Regions (SAR). A SAR is part of a department (a major French administrative entity) which exhibits an agro-ecological homogeneity. This consistency from both the ecological and economic points of view makes the SAR scale well suited for our bio-economic modeling. The model described below is built for each SAR.

To assess the ecological performance, we decided to focus on common bird populations and related indicators (Gregory *et al.* 2004). Although the metric and the characterization of biodiversity remain an open debate (Millennium Ecosystem Assessment 2005), this choice is justified for several reasons (Ormerod & Watkinson 2000). (i) Birds lie at a high level in the trophic food chains and thus capture the variations in the chains. (ii) Birds provide many ecological services, such as the regulation of rodent populations and pest control, thus justifying our interest in their conservation and viability (Sekercioglu *et al.* 2004). (iii) Their close vicinity to humans makes them a simple and comprehensive example of biodiversity for a large audience of citizens and politics.

The French Bird Breeding Survey (FBBS) database<sup>1</sup> provided the informations related to the bird abundances across the whole country. Abundance values for each species were available for the period 2002-2008. For each species, we further performed a spatial interpolation of these abundance data to obtain relative abundance values for each possible square in the country (e.g. 136 000 squares) using kriging models based on spatial autocorrelation and the exponential function (Doxa *et al.* 2010). We then averaged the abundance values at the SAR scale. Among the species monitored by this large-scale long-term survey, we selected 14 generalist species and 20 farmland specialist species which have been classified according to their habitat requirements at a Europe scale (European Bird Census Council 2007). Table 1 lists the 14 generalist species and the 20 farmland specialist species used as a reference for the European Farmland Bird Index FBI (Gregory *et al.* 2004). Previous analyses have shown the relevance of the national FBI to reflect the response of farmland biodiversity to agricultural intensification (Doxa *et al.* 2010, Mouysset *et al.* 2012a).

For agro-economic data, we use the French agro-economic classification OTEA developed by the French Farm Accounting Data Network (FADN)<sup>2</sup> and the Observatory of Rural Development (ODR)<sup>3</sup>. This organization classify the land

---

<sup>1</sup>See the Vigie-Nature website <http://www2.mnhn.fr/vigie-nature/>. Standardized monitoring of spring-breeding birds at 1747 2 \* 2 km<sup>2</sup> plots across the whole country. Details of the monitoring method and sampling design can be found in Jiguet (2009).

<sup>2</sup><http://ec.europa.eu/agriculture/rica/>

<sup>3</sup><https://esrcarto.supagro.inra.fr/intranet/>

uses in 14 classes of agricultural systems denoted by OTEA (see tab. 2). Each SAR is a specific combination of these OTEA. The surfaces dedicated to each of the 14 OTEA and the associated gross margins relying on tax return, for the years 2002 to 2008 are available on the ODR website. The budgetary constraint is calibrated with the current French Common Agricultural Policy budget.

As depicted in figure 1, the bio-economic model is composed of three compartments with a multi-scale perspective as in Mouysset *et al.* (2011): the public policy at large (national) scale interacts with the farming land-uses and biodiversity dynamics at local (SAR) scale.

## 2.2. The biodiversity model

The biodiversity model deals with a community of species instead of focusing on emblematic species. It is based on population dynamics with intra-specific competition depending on habitat and especially on farming land-use. A Beverton-Holt function is selected for sake of simplicity. It captures intra-specific competition through a carrying capacity parameter as follows:

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

where  $N_{s,r}(t)$  stands for the abundance of species  $s$  in region  $r$  at year  $t$ . The  $R_{s,r}$  coefficient corresponds to the intrinsic growth rate specific to a given species  $s$  in region  $r$ . The product  $M_{s,k}(t) * R_{s,r}$  represents the carrying capacity of the habitat  $r$  and the value  $M_{s,k}(t)$  captures the ability of the habitat  $r$  to host the species  $s$ . The habitat parameter  $M_{s,r}(t)$  is assumed to depend on the agricultural systems  $k$  as follows:

$$M_{s,r}(t) = \beta_{s,r} + \sum_k \alpha_{s,r,k} \cdot A_{r,k}(t) \quad (2)$$

where  $A_{r,k}(t)$  represents the shares of the Utilized Agricultural Area 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, inform on how such species  $s$  responds to agricultural land-use  $k$  in a region  $r$ . The  $\beta_{s,r}$  coefficient can be interpreted as the mean habitat coefficient for a species  $s$  in a region  $r$  and integrates others factors such as the proportion of forests or urban areas. The coefficients  $\alpha_{s,r}$  and  $\beta_{s,r}$  are calibrated according to a least-square method (see Mouysset *et al.* (2012b)).

The population size  $\tilde{N}_{s,r}(t+1)$  is estimated with the population size computed by the model  $N_{s,r}(t+1) = f(N_{s,r}(t))$  and a uncertainty coefficient  $\vartheta_{s,r}(t)$ :

$$\tilde{N}_{s,r}(t+1) = f(N_{s,r}(t)) + \vartheta_{s,r}(t) \quad (3)$$

The random variables  $\vartheta_{s,r}(t)$  captures the ecological stochasticity affecting the dynamics. The variables  $\vartheta_{s,r}(t)$  are coming from Gaussian distributions calibrated with the variance of the historical abundances compared to the computed abundances in the time series.

### 2.3. The economic model

Each region is represented by a standard agent. Agent income in region  $r$  at year  $t$  denoted by  $Inc_r(t)$  relies on the expected gross margin per unit of scale  $gm_{r,k}$ , current proportions of the Utilized Agricultural Area (UAA) dedicated to the agricultural systems  $A_{r,k}(t)$  and incentives  $\tau_k$  (taxes with  $\tau_k < 0$  or subsidies with  $\tau_k > 0$ ) which takes form of a percentage of gross margins as follows:

$$Inc_r(t) = \sum_k gm_{r,k} \cdot A_{r,k}(t) \cdot (1 + \tau_k) \quad (4)$$

Gross margins  $gm_{r,k}(t)$  are supposed to be uncertain. The variability on gross margins includes both market, production and climate uncertainties. A Gaussian distribution parametrized with the mean and the covariance matrix of the historical data is chosen to capture such uncertainties. Also assumed is a quadratic form for the utility function of the representative agent (Lien 2002). Hence, the utility  $U_r(t)$  for the representative farmer corresponds to the difference between an expected income  $\mathbb{E}[Inc_r(t)]$  and its risky part  $\text{Var}[Inc_r(t)]$ :

$$U_r(t) = \mathbb{E}[Inc_r(t)] - a \cdot \text{Var}[Inc_r(t)] \quad (5)$$

with

$$\mathbb{E}[Inc_r(t)] = \sum_k \overline{gm}_{r,k} \cdot A_{r,k}(t) \cdot (1 + \tau_k) \quad (6)$$

$$\text{Var}[Inc_r(t)] = \sum_k \sum_{k'} \sigma_{r,k,k'}(t) \cdot A_{r,k}(t) \cdot A_{r,k'}(t) \cdot (1 + \tau_k) \cdot (1 + \tau_{k'}) \quad (7)$$

Expected gross margins  $\overline{gm}_{r,k}$  are the mean of the 7 historical years<sup>4</sup>. The coefficient  $a$  represents the risk aversion level of the farmer: the higher the  $a$ , more risk-averse the farmer. The risky term is computed with the covariance<sup>5</sup>  $\sigma_{r,k,k'}$  between margins of agricultural systems  $k$  and  $k'$  in region  $r$ . For each year  $t$ , the regional standard agents choose their agricultural land-uses  $A_{r,k}(t)$  in order to maximize their income utility in an uncertain context (eq. 8) according to rigidity (eq. 9) and rigidity constraints (eq. 10). This approach refers to the framework of maximization under constraints as in Polasky *et al.* (2005), Pacini *et al.* (2004), Drechsler *et al.* (2007), Mouysset *et al.* (2011).

$$\max_{A_{r,1}; \dots; A_{r,14}} U_r(t) \quad (8)$$

When maximizing the utility, the standard agent must comply with two con-

---

<sup>4</sup>  $\overline{gm}_{r,k} = \frac{1}{7} \sum_{t=1}^{t=7} gm_{r,k}(t)$ .

<sup>5</sup>  $\sigma_{r,k,k'} = \frac{1}{7} \sum_{t=1}^{t=7} (gm_{r,k}(t) - \overline{gm}_{r,k}(t)) \cdot (gm_{r,k'}(t) - \overline{gm}_{r,k'}(t))$ .

straints at every point in time:

$$|A_{r,k}(t) - A_{r,k}(t-1)| \leq \varepsilon \cdot A_{r,k}(t-1) \quad (9)$$

$$\sum_k A_{r,k}(t) = UAA_r(t_0) \quad (10)$$

The rigidity constraint (9) restricts the area that the farmer can modify at each time for each agricultural system  $k$ . The parameter  $\varepsilon$  captures change costs or inertia. The constraint (10) ensures that the total utilized agricultural area (UAA) is kept fixed. The parameters  $a$  and  $\varepsilon$  are calibrated according to a least-square method (see Mouysset *et al.* (2012b)).

#### 2.4. The bio-economic indicators

##### 2.4.1. The ecological indicators

The indicators used to assess the ecological performances are computed through the abundances  $\tilde{N}_{s,r}(t)$  of the species at play. As suggested by Mouysset *et al.* (2012a), the community are analyzed through the combination of the Farmland Bird Index (FBI), the Community Specialization Index (CSI) and the Community Trophic Index (CTI). The Farmland Bird Index, which measures the growth of the farmland specialist community, has been adopted by the European Community as the official environmental index especially to analyze structural changes in biodiversity (Balmford *et al.* 2003). The relevance of the FBI to reflect the response of farmland biodiversity to agriculture intensification has been shown in Doxa *et al.* (2010). In this aggregated index, the abundances variation of each species is taken into account similarly, independently from the abundance value. We first estimated a national population index for each species from the abundances values of all SAR  $r$  (eq. 11), then we calculated the aggregated indicator  $FBI_{Nat}$  (eq. 12).

$$\tilde{N}_{s,Nat}(t) = \sum_r \tilde{N}_{s,r}(t) \quad (11)$$

$$FBI_{Nat}(t) = \prod_{s \in Specialist} \left( \frac{\tilde{N}_{s,Nat}(t)}{\tilde{N}_{s,Nat}(2008)} \right)^{1/20} \quad (12)$$

The Community Trophic Index (CTI) informs on the average trophic level of a community as in Pauly *et al.* (1998). The CTI integrates both the generalist species and the farmland specialist species (table 1). This indicator classifies the communities with more granivorous species (e.g. low trophic level) against the communities with more insectivorous and carnivorous species (e.g. high trophic level) (Mouysset *et al.* 2012a). It is computed as the weighted arithmetic mean of the exponential of the species trophic level balanced by the abundances (eq. 13 and 14). An exponential function is used to better contrast communities with or without bird individuals of the higher trophic levels. National  $CTI_{Nat}$  is the arithmetic mean of the 620 regional  $CTI_r$  (eq. 15).



$$\tilde{N}_{tot,r}(t) = \sum_s N_{s,r}(t) \quad (13)$$

$$CTI_r(t) = \sum_s \frac{\tilde{N}_{s,r}(t)}{\tilde{N}_{tot,r}(t)} \cdot \exp(STI_s) \quad (14)$$

$$CTI_{Nat}(t) = \frac{1}{620} \cdot \sum_r CTI_r(t) \quad (15)$$

Finally, the Community Specialization Index (CSI) leads to interpret the response of the composition of local bird communities to agricultural pressures (Barnagaud *et al.* 2011). A habitat specialization species index (SSI) has been computed for each species, reporting the coefficient of variation of the abundance of a species across 18 habitat categories (see Julliard *et al.* (2006)). This index measures the average degree of habitat specialization among the individuals of the community. It leads to discriminating 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, the local  $CSI_r$  is then calculated as the arithmetic mean of the species specialisation index weighted by the abundances (eq. 13 and 16). National  $CSI_{Nat}$  is the arithmetic mean of the 620 regional  $CSI_r$  (eq. 17).

$$CSI_r(t) = \sum_s \frac{\tilde{N}_{s,r}(t)}{\tilde{N}_{tot,r}(t)} \cdot SSI_s \quad (16)$$

$$CSI_{Nat}(t) = \frac{1}{620} \cdot \sum_r CSI_r(t) \quad (17)$$

#### 2.4.2. The economic indicators

The economic performances of the farmers are measured with the national income which is computed as follows:

$$\overline{Inc}_{nat}(t) = \frac{1}{A_{nat}} \sum_{r=1}^{620} A_r \cdot Inc_r(t) \quad (18)$$

where  $A_{nat} = \sum_{r=1}^{620} A_r$  is the total surface of SAR over France.

Hereafter, the public budget plays a major role for the viability analysis. This budget  $Budg(t)$  is computed according to the different incentives  $\tau_k$  as follows:

$$Budg(t) = \sum_r \sum_k S_r \cdot gm_{r,k} \cdot A_{r,k}(t) \cdot \tau_k \quad (19)$$

### 3. The co-viability scenarios

We now examine the bio-economic sustainability of the agro-ecological system through a viability approach. The CVA approach (Co-Viability Analysis) considers both biodiversity and economic viability objectives through a large set of constraints that have to be satisfied. Here the constraints have to be satisfied in the probabilistic sense as in De Lara & Doyen (2008), Doyen & De Lara (2010), Doyen *et al.* (2012). Given a confidence rate, the viable kernel allows to identify different public policies and scenarios with admissible agro-ecological risk. We now describe the different constraints taken into account hereafter. They basically relies on a comparison with the Statu Quo (SQ) scenario which corresponds to the performances obtained if we fixed the land-uses to the 2008 land-uses. In others words:

$$A_{r,k}^{SQ}(t) = A_{r,k}(2008), \quad t = 2009, \dots, T \quad (20)$$

#### 3.1. Ecological constraints

By ecological constraints is meant guaranteed levels for different biodiversity indices. Three indicators which has been identified in (Mouysset *et al.* 2012a) as relevant to characterize the state of bird community in response of agricultural public policies capture the biodiversity scores: the Farmland Bird Index  $FBI(t)$ , the Community Specialization Index  $CSI(t)$  and the Community Trophic Index  $CTI(t)$ . The lower thresholds for the constraints are based on the performances  $FBI^{SQ}(t)$ ,  $CTI^{SQ}(t)$ ,  $CSI^{SQ}(t)$  obtained with a Statu Quo (SQ) scenario as defined by relation (20).

$$FBI(t) \geq \lambda * FBI^{SQ}(t) \quad (21)$$

$$CTI(t) \geq \lambda * CTI^{SQ}(t) \quad (22)$$

$$CSI(t) \geq \lambda * CSI^{SQ}(t) \quad (23)$$

where the rate  $\lambda$  measures the strength of the constraint. Typically, three levels are tested among  $\lambda = 0.95$ ,  $\lambda = 0.97$  and  $\lambda = 1$ .

#### 3.2. Economic constraints

Similarly, from the economic viewpoint, viability requires that the incomes  $Inc(t)$  derived from farming activities are not worst than the current or SQ level  $Inc^{SQ}(t)$  derived from relation (20):

$$Inc(t) \geq \lambda * Inc^{SQ}(t) \quad (24)$$

It is also required that the public policy scenarios are always complying with a budgetary rule (eq. 25).

$$Budg(t) \leq Budg(2008) \quad (25)$$

In other words, the spending public budget at each time  $t$  does not exceed the spending current budget at time 2008.

### 3.3. Viable incentives

The public policy in this study are based on incentives  $\tau$  (subsidies and taxes) distributed to the different agricultural system  $k$ . Bio-economic performances in response to these scenarios are computed from 2009 to 2050 according to the ecological and economic models described above.

For accelerating the numerical computations, the public decision variables  $\tau$  are restricted to only two incentives: the cereal incentive  $\tau_{cop}$  is dedicated to arable lands (Otea (1) in table 2) and the grassland incentive  $\tau_{grass}$  is applied to non-intensive grassland systems (Otea (4), (5), (6), (7) in table 2).

We choose to deal with uncertainty in a probabilistic sense. We therefore perform a stochastic viability analysis. For this, we consider a probability  $\mathbb{P}$  on scenarios  $\omega(\cdot) \in \Omega$ . For each public scenario  $\tau$ , we compute the probability to satisfy in an uncertain context the different bio-economic constraints:

$$CVA(\tau) = \mathbb{P} \left( \text{Constraints (21), (22), (23), (24) and (25), holds for } t = 2009 \dots 2050 \right) \quad (26)$$

Given a confidence rate  $\beta \in ]0, 1]$ , we aim at identifying the controls  $(\tau_{cop}, \tau_{grass})$  that satisfy the following condition<sup>6</sup>:

$$CVA(\tau) \geq \beta \quad (27)$$

In terms of decision, given a level of risk  $1 - \beta$ , we aim at identifying viable incentives, namely  $\tau = (\tau_{cop}, \tau_{grass})$  that satisfy viability condition (26). In this context, of particular interest are the controls that maximize the viability probabilities, that is  $\max_{\tau} CVA(\tau)$ . Given a level of risk  $1 - \beta$ , we define the viable decision kernel  $\mathcal{T}_{viable}^{\beta}$  by:

$$\mathcal{T}_{viable}^{\beta} = \{ \tau, CVA(\tau) \geq \beta \} \quad (28)$$

As we are in uncertain context, the outcomes of every incentive scenario  $\tau = (\tau_{grass}, \tau_{cop})$  are generated 100 times to approximate its viability probability  $CVA(\tau)$ . Gaussian and i.i.d. assumptions are considered for random variables  $\vartheta(t)$  and  $gm(t)$  introduced in eq. (4) and eq. (1) respectively.

---

<sup>6</sup>In a more formal way, stochastic viability analysis refers to the identification of the stochastic viability kernel  $viab_{\beta}$  (De Lara & Doyen 2008) defined as

$$viab_{\beta}(t_0) = \{ N(t_0) \mid \exists \tau \text{ } CVA(\tau) \geq \beta \}.$$

## 4. Results

### 4.1. Public policies combining bio-economic constraints

For each tested public policy  $\tau = (\tau_{grass}, \tau_{cop})$ , the figure 2 represents the probability (CVA( $\tau$ )) to satisfy the constraint along the trajectories: the more blue the scenario is, the higher the probability to verify the constraints in an uncertain context. The figure 2 shows the kernel of public policies  $\mathcal{T}_{viab}$  which insures the budgetary constraint and at least 0.95 % ( $\lambda = 0.95$ ) of the bio-economic performances obtained with the Statu Quo scenario (according to the income, FBI, CTI and CSI constraints). This figure highlights that it exists a large viable set of public policies  $\mathcal{T}_{viab}$  satisfying simultaneously economic and ecological performances. We observe that this viable kernel  $\mathcal{T}_{viab}$  is roughly based on subsidies for non intensive grasslands ( $\tau_{grass} \geq 0$ ) and taxes for crops ( $\tau_{cop} \leq 0$ ). However, the incentives can relatively vary within this kernel ( $0.3 \leq \tau_{grass} \leq 0.6$  and  $-0.2 \leq \tau_{cop} \leq -0.6$ ) by keeping the same bio-economic risk. Moreover, the uncertainty management is satisfying since a part of this kernel (in dark blue) complies with the constraints with a high confidence rate ( $\beta = 0.98\%$ ).

### 4.2. Bio-economic sensitivity

The figure 3 compares the kernel of public policies under increasing economic constraint in the one hand, and under increasing FBI constraint in the other hand. With the economic constraint only (eq. 24), we observe the viability kernel  $\mathcal{T}_{viab}$  is the upper triangle beyond a negative trade-off between crop and grassland incentives. If the crop subsidies  $\tau_{cop}$  decrease, the grassland incentives  $\tau_{grass}$  have to be increased to maintain the same level of income. When the economic objective is more demanding (i.e.  $\lambda$  is increased in eq. 24), the trade-off is moved upward. This means that if we want to keep the same level of grassland subsidies, the crop subsidies need to be increased to ensure the economic constraint.

With the FBI constraint only (eq. 21), the set of viable public policies  $\mathcal{T}_{viab}$  is broadly smaller and it corresponds to lower triangle under a positive trade-off between the two incentives ( $\tau_{grass}$  and  $\tau_{cop}$ ): if the crop subsidies decrease, the grassland subsidies can decrease. When the FBI constraint is more stringent (i.e.  $\lambda$  is increased in eq. 21), the positive trade-off is moved downward. In others words, to keep the same level of grassland subsidies with the FBI constraint, the crop subsidies have to be smaller (i.e. the crop taxes have to be higher).

More generally, the figure 3 shows that there exists viability kernels  $\mathcal{T}_{viab}$  for both economic and ecological constraints. However, these kernels reduces with the viability requirements and constraint levels. These reductions are going in opposite way according to the economic or ecological constraint. Whatever the constraint, the management of risk is satisfying with the existence of public policies with a probability of success at  $\lambda = 0.98$  (in dark blue) in the center of the viability kernel: the viable decision kernel  $\mathcal{T}_{viab}^{0.98}$ .

### 4.3. Ecological sensitivity

The figure 4 displays the viable public policies  $\mathcal{T}_{viab}$  under increasing ecological constraints (i.e.  $\lambda$  is increased in eq. 21, 22, 23) keeping the same economic constraint (i.e.  $\lambda$  is constant in eq. 24). We clearly observe that the FBI constraint is the more restrictive ecological constraint. For the same strength  $\lambda$  of constraint, the kernel obtained with the FBI constraint is smaller than those obtained with the CTI and CSI constraints.

For the intermediary constraint ( $\lambda = 0.97$ ), the management of risk is decreased with the FBI constraint. Indeed if the viability kernel  $\mathcal{T}_{viab}$  exists, the part in dark blue which insures a dark probability of success ( $\beta=98\%$ ) is quite missing.

With the more stringent constraints ( $\lambda = 1$ ), the viability kernel  $\mathcal{T}_{viab}$  is empty for the three ecological constraints. In other terms, it is not possible to maintain at least the inter-temporal bio-economic performances obtained with the Statu Quo scenario in this ecological-economic uncertain context.

### 4.4. Trajectories and land-uses

The figures 5 and 6 present four examples of trajectories with the associated constraint at 95% ( $\lambda = 0.95$ ) for the two more stringent criteria: the income and the FBI. The income satisfies the constraint in three cases (fig. 5b, 5c, 5d). Only the scenario with taxes on both grasslands and crops (fig. 5a) violates the constraint at the beginning of the trajectory.

According to the FBI, only the scenario coupling taxes on crops and subsidies on grassland verifies the constraint (fig. 6d). This scenario ( $\tau_{grass} = 0.6$  and  $\tau_{cop} = -0.2$ ) is thus the only viable public policy among the four presented scenarios according the both economic and ecological criteria.

The figure 7 compares the land-uses for the four scenarios and the Statu Quo scenario. This figure illustrates the substitution of the crops by the non intensive grasslands in viable scenarios.

## 5. Discussion

### 5.1. Decision support for agriculture and farmland biodiversity

This study highlights that it exists a set of sustainable public policy scenarios able to reconcile biodiversity and agriculture. The management of uncertainty is satisfying since several policies comply with the set of inter-temporal constraints with a high probability. In terms of biodiversity, these public decisions warrant the persistence of the community. The viability of the community should sustain ecosystemic services, which should indirectly contribute to the farming production and to its sustainability.

We have showed that the viable policies are based on a combination between taxes on crops and subsidies on extensive and semi-extensive grasslands. This conclusion confirms the requirement to develop grasslands and reduce crops for a sustainable management of agriculture and biodiversity (Potter & Goodwin 1998). Indeed, the development of grasslands is positive for biodiversity (Laiolo

2005). And relevant subsidy scenarios can make this agriculture perspective economically viable (Mouysset *et al.* 2011). Moreover the size of the kernel with various combinations between the two incentives offers an additional flexibility to integrate others constraints such as social objectives.

As suggested by Mouysset *et al.* (2012a), we integrate the three indicators FBI , CSI and CTI as ecological criteria of biodiversity. The sensitivity analysis shows that the FBI is the more sensitive and the more restrictive criteria. In others terms, by sustaining the FBI , the three ecological constraints are satisfied. This observation validates the choice of this indicator by the European Union as indicator of structural biodiversity changes in response to agricultural evolution (Balmford *et al.* 2003) even if this is not the more relevant in functional terms.

### 5.2. *The co-viability approach for sustainability issues*

Let us analyze the whole set of results in terms of sustainability. We built in this study a dynamic bio-economic modeling to represent the agro-ecosystem. This model combines multi-species and multi-scale considerations. The study of this modeling through the viability approach (Aubin 1991) has lead to identify public policies for multi-functional and sustainable agriculture.

Beyond the analysis on the case study, this work advocates an integrated and multi-criteria approach involving many scientific disciplines, in broad collaborative efforts. A wide range of stakeholders are involved in agro-ecological issues. Each of these groups has an interest in particular outcomes and the outcomes that are considered desirable by one stakeholder may be undesirable to another group. The consideration of this multi-dimensional nature of farming management is a way of guaranteeing a reasonable exploitation of terrestrial resources, allowing the creation of conditions for sustainability from economic, environmental and social viewpoints. The present work is in direct line with these considerations.

First, of interest is the use of bio-economic models and assessments articulating ecological and socio-economic processes and goals as in Béné *et al.* (2001), Doyen *et al.* (2012), Péreau *et al.* (2012). More generally, this study confirms the use of this viability method as a convenient tool to reconcile apparently contradictory objectives. Indeed, many studies based on optimum-control approaches have identified a Pareto-optimum frontier between ecological and economic performances of agriculture (Polasky *et al.* 2005, Barraquand & Martinet 2011). In others words, it does not exist a unique win-win scenario which maximizes simultaneously ecological and economic criteria. This viability approach offers a more flexible context of sustainability which lead to reconcile different objectives.

Moreover by focusing on sustainability and viability, the present model exhibits management strategies and scenarios which satisfy different constraints at each time. With these considerations, the model is taken accounts for intergenerational equity and allows a conciliation between the present and the future. By identifying current public policy decisions which avoids future crisis without penalizing the current generation, the viability approach is in direct line with definition of the sustainability. As emphasized in Martinet & Doyen

(2007) and De Lara & Doyen (2008), viability is closely related to the maximin (Rawlsian) approach with respect to intergenerational equity. In this respect, the co-viability strategy turns out to be a promising approach.

### Acknowledgements

This work was carried out with the financial support of the "ANR - Agence Nationale de la Recherche- The French National Research Agency" under the "Systerra program - Ecosystems and Sustainable Development," project "ANR-08-STRA-007,FARMBIRD-Coviability models of FARMing and BIRD biodiversity."

### References

- Alavalapati, J.R.R., Stainback, G.A., & Carter, D.R. 2002. Restoration of the longleaf pine ecosystem on private lands in the US South: an ecological economic analysis. *Ecological Economics*, **40**(3), 411–419.
- Aubin, J.P. 1991. *Viability Theory*.
- Balmford, A., Green, R.E., & Jenkins, M. 2003. Measuring the changing state of nature. *Trends in Ecology & Evolution*, **18**(7), 326–330.
- Barnagaud, J-Y., Devictor, V., Jiguet, F., & Archaux, F. 2011. When species become generalists: on-going large-scale changes in bird habitat specialization. *Global Ecology and Biogeography*, **20**(4), 630–640.
- Barraquand, F., & Martinet, V. 2011. Biological conservation in dynamic agricultural landscapes: Effectiveness of public policies and trade-offs with agricultural production. *Ecological Economics*, **70**(5), 910–920.
- Baumgärtner, Stefan, & Quaas, Martin F. 2009. Ecological-economic viability as a criterion of strong sustainability under uncertainty. *Ecological Economics*, **68**(7), 2008–2020.
- Béné, C., Doyen, L., & Gabay, D. 2001. A viability analysis for a bio-economic model. *Ecological Economics*, **36**(3), 385–396.
- Benton, T. G., Bryant, D. M., Cole, L., & Crick, H. Q. P. 2002. Linking agricultural practice to insect and bird populations: a historical study over three decades. *Journal of Applied Ecology*, **39**(4), 673–687.
- Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., & Scharlemann, J. P. W. 2010. Global Biodiversity: Indicators of Recent Declines. *Science (New York, N.Y.)*, **1164**(Apr.).
- Butler, S.J., Brooks, D., Feber, R.E., Storkey, J., Vickery, J.A., & Norris, K. 2009. A cross-taxonomic index for quantifying the health of farmland biodiversity. *Journal of Applied Ecology*, Sept., 1154–1162.

- Cury, P., Mullon, C., Garcia, S., & Shannon, L. 2005. Viability theory for an ecosystem approach to fisheries. *ICES Journal of Marine Science*, **62**(3), 577–584.
- De Lara, M., & Doyen, L. 2008. *Sustainable Management of Natural Resources. Mathematical Models and Methods*. Springer-v edn.
- De Lara, M., Doyen, L., Guilbaud, T., & Rochet, M-J. 2007. Is a management framework based on spawning-stock biomass indicators sustainable? A viability approach. *ICES Journal of Marine Science*, **64**(4), 761–767.
- Diamond, P. A., & Hausman, J. A. 1994. Contingent valuation: Is some umber better than no number? *Journal of Economic Perspectives*, **8**(4), 45–64.
- Doherty, P. F. Jr., Marschall, E. A., & Grubb, T. C. Jr. 1999. Balancing conservation and economic gain: a dynamic programming approach. *Ecological Economics*, **29**(3), 349–358.
- Donald, P. F., Green, R. E., & Heath, M. F. 2001. Agricultural intensification and the collapse of Europe’s farmland bird populations. *Proceedings. Biological sciences / The Royal Society*, **268**(1462), 25–9.
- Doxa, A., Bas, Y., Paracchini, M-L., Pointereau, P., Terres, J-M., & Jiguet, F. 2010. Low-intensity agriculture increases farmland bird abundances in France. *Journal of Applied Ecology*, Sept., no–no.
- Doyen, L., & De Lara, M. 2010. Stochastic viability and dynamic programming. *Systems & Control Letters*, **59**(10), 629–634.
- Doyen, L., De Lara, M., Ferraris, J., & Pelletier, D. 2007. Sustainability of exploited marine ecosystems through protected areas: A viability model and a coral reef case study. *Ecological Modelling*, **208**(2-4), 353–366.
- Doyen, L., Thébaud, O., Béné, C., Martinet, V., Gourguet, S., Bertignac, M., Fifas, S., & Blanchard, F. 2012. A stochastic viability approach to ecosystem-based fisheries management, *Ecological Economics*.
- Drechsler, M. 2001. The importance of economic costs in the development of guidelines for spatial conservation management. *Biological Conservation*, **97**(1), 51–59.
- Drechsler, M., Watzold, F., Johst, K., Bergmann, H., & Settele, J. 2007. A model-based approach for designing cost-effective compensation payments for conservation of endangered species in real landscapes. *Biological Conservation*, **140**(1-2), 174–186.
- European Bird Census Council. 2007. *The state of Europe s Common Birds ?* Ebcc edn. The state of Europe s Common Birds ?



- Flowerdew, J. R., & Kirkwood, R. C. 1997. Mammal biodiversity in agricultural habitats. *Pages 25–40 of: BCPC Publications (ed), Biodiversity and Conservation in Agriculture. BCPC Symposium Proceedings. No 69.* Alton.
- Gatto, M., & De Leo, G. A. 2000. Pricing biodiversity and ecosystem services: The never-ending story. *Bioscience*, **50**(2), 347–355.
- Gregory, R. D., G. Noble, D., & Custance, J. 2004. The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom. *Ibis*, **146**(Nov.), 1–13.
- Groot, J., Rossing, W., Jellema, A., Stobbelaar, D., Renting, H., & Vanittersum, M. 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality -A methodology to support discussions on land-use perspectives. *Agriculture, Ecosystems & Environment*, **120**(1), 58–69.
- Havlik, P., Veysset, P., Boisson, J. M., Lherm, M., & Jacquet, F. 2005. Joint production under uncertainty and multifunctionality of agriculture: policy considerations and applied analysis. *European Review of Agricultural Economics*, **32**(4), 489–515.
- Holkamper, A., & Seppelt, R. 2007. Evaluating cost-effectiveness of conservation management actions in an agricultural landscape on a regional scale. *Biological Conservation*, **136**(1), 117–127.
- Irwin, E. G., & Geoghegan, J. 2001. Theory, data, methods: developing spatially explicit economic models of land use change. *Agriculture, Ecosystems & Environment*, **85**(1-3), 7–24.
- Jiguet, F. 2009. Method-learning caused first-time observer effect in a newly-started breeding bird survey. *Bird Study*, **56**(2), 253–258.
- Jiguet, F. 2010. *Les résultats nationaux du programme STOC de 1989 à 2009.*
- Julliard, R., Clavel, J., Devictor, V., Jiguet, F., & Couvet, D. 2006. Spatial segregation of specialists and generalists in bird communities. *Ecology letters*, **9**(11), 1237–44.
- Kleijn, D., Baquero, R. A., Clough, Y., Díaz, M., De Esteban, J., Fernández, F., Gabriel, D., Herzog, F., Holzschuh, A., Jöhl, R., Knop, E., Kruess, A., Marshall, E. J. P., Steffan-Dewenter, I., Tscharrntke, T., Verhulst, J., West, T. M., & Yela, J. L. 2006. Mixed biodiversity benefits of agri-environment schemes in five European countries. *Ecology letters*, **9**(3), 243–54; discussion 254–7.
- Krebs, J. R., Wilson, J. D., Bradbury, R. B., & Siriwardena, G. M. 1999. A second silent spring? *Trends in ecology & evolution*, **10**(7), 264–6.

- Laiolo, P. 2005. Spatial and seasonal patterns of bird communities on Italian agroecosystems. *Conservation Biology*, **19**(1), 1547–1556.
- Lien, G. 2002. Non-parametric estimation of decision makers' risk aversion. *Agricultural Economics*, **27**(1), 75–83.
- Martinet, V., & Doyen, L. 2007. Sustainability of an economy with an exhaustible resource: A viable control approach. *Resource and Energy Economics*, **29**(1), 17–39.
- Martinet, V., Thébaud, O., & Doyen, L. 2007. Defining viable recovery paths toward sustainable fisheries. *Ecological Economics*, **64**(2), 411–422.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well being: current state and trends. Chapter 26 : cultivated systems.*
- Mouysset, L., Doyen, L., Jiguet, F., Allaire, G., & Leger, F. 2011. Bio economic modeling for a sustainable management of biodiversity in agricultural lands. *Ecological Economics*, **70**(4), 617–626.
- Mouysset, L., Doyen, L., & Jiguet, F. 2012a. Different policy scenarios to promote various targets of biodiversity. *Ecological Indicators*, **14**(1), 209–221.
- Mouysset, L., Doyen, L., & Jiguet, F. 2012b. *How does the economic risk aversion affect biodiversity ?*
- Ormerod, S. J., & Watkinson, A. R. 2000. Editors' Introduction: Birds and Agriculture. *Journal of Applied Ecology*, **37**(5), 699–705.
- Pacini, C., Wossink, A., Giesen, G., & Huirne, R. 2004. Ecological-economic modelling to support multi-objective policy making: a farming systems approach implemented for Tuscany. *Agriculture, Ecosystems & Environment*, **102**(3), 349–364.
- Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., & Torres, F.Jr. 1998. Fishing Down Marine Food Webs. *Science*, **279**(5352), 860–863.
- Péreau, J-C., Doyen, L., Little, L. R., & Thébaud, O. 2012. The triple bottom line: Meeting ecological, economic and social goals with Individual Transferable Quotas. *Journal of Environmental Economics and Management*.
- Polasky, S., Nelson, E., Lonsdorf, E., Fackler, P., & Starfield, A. 2005. Conserving species in a working landscape: land use with biological and economic objectives. *Ecological Applications*, **15**(6), 2209–2209.
- Potter, C., & Goodwin, P. 1998. Agricultural Liberalization . in the European Union : An Analysis of the Implications for Nature Conservation. *Management*, **14**(3), 287–298.

- Rashford, B. S., Dugger, B. D., & Adams, R. M. 2008. Application of a Bio-economic Production Model to Improve Wildlife Management. *Journal of Wildlife Management*, **72**(2), 510–517.
- Sabatier, R., Doyen, L., & Tichit, M. 2012. Action Versus Result-Oriented Schemes in a Grassland Agroecosystem: a Dynamic Modelling Approach. *Plos One*.
- Sekercioglu, C. H., Daily, G. C., & Ehrlich, P. R. 2004. Ecosystem consequences of bird declines. *Proceedings of the National Academy of Sciences of the United States of America*, **101**(52), 18042–7.
- Shi, T., & Gill, R. 2005. Developing effective policies for the sustainable development of ecological agriculture in China: the case study of Jinshan County with a systems dynamics model. *Ecological Economics*, **53**(2), 223–246.
- Sotherton, N. W., & Self, M. J. 2000. Changes in plant and arthropod biodiversity on lowland farmland: an overview. *Pages 26–35 of: Aebischer, NJ; Evans, AD; Grice, PV; Vickery, JA (ed), Spring Conference of the British-Oornithologists-Union*.
- Swihart, R. K., Moore, & Jeffrey, E. 2003. *Conserving Biodiversity in Agricultural Landscapes Model-Based Planning Tools*. Purdue University press.
- Tichit, M., Doyen, L., Lemel, J., Renault, O., & Durant, D. 2007. A co-viability model of grazing and bird community management in farmland. *Ecological Modelling*, **206**(3-4), 277–293.
- van Wenum, J. H., Wossink, G. A. A., & Renkema, J. A. 2004. Location-specific modeling for optimizing wildlife management on crop farms. *Ecological Economics*, **48**(4), 395–407.
- Vickery, J. A., Bradbury, R. B., Henderson, I. G., Eaton, M. A., & Grice, P. V. 2004. The role of agri-environment schemes and farm management practices in reversing the decline of farmland birds in England. *Biological Conservation*, **119**(1), 19–39.

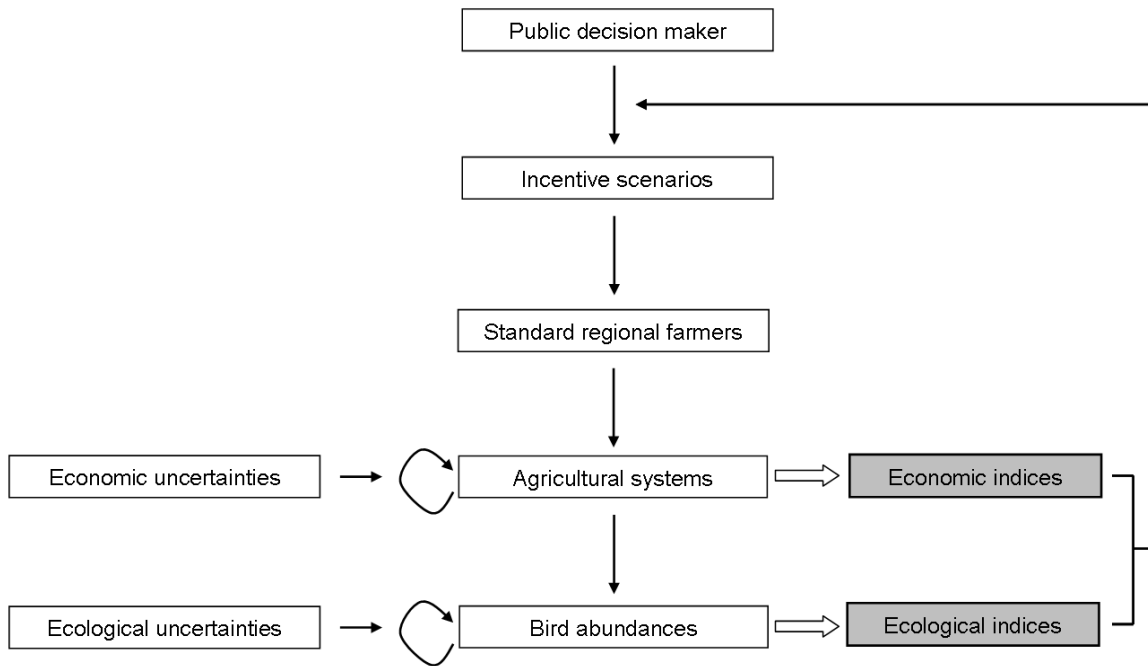


Figure 1: Bio-economic model coupling. The decision maker determines an incentive scenarios which affect farmer's decisions. The farmers choose their agricultural systems by maximizing their utility function under technical constraints. These choices affect the habitat and the bird communities.

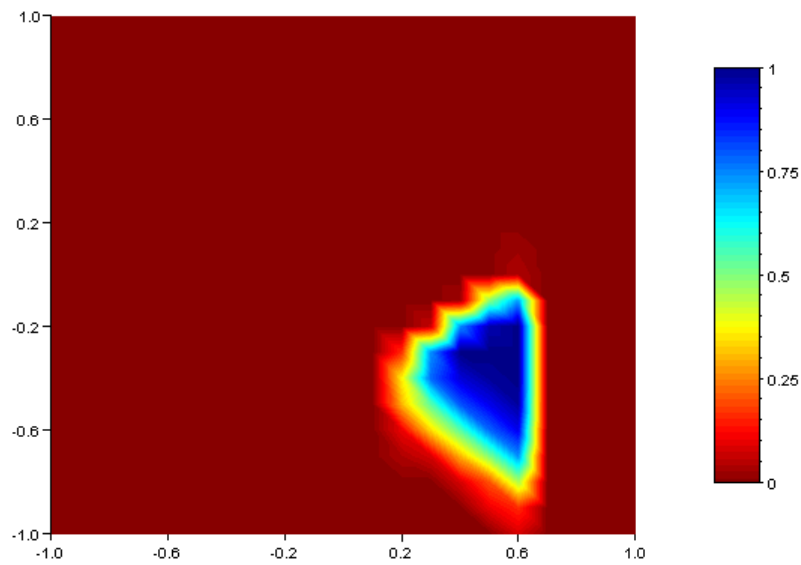


Figure 2: Probability of the different public policies scenarios to satisfy the set of constraints (budgetary, income, FBI, CTI and CSI constraints) with  $\lambda = 0.95$  in an uncertain context. The x-axis stands for the  $\tau_{grass}$  incentives and the y-axis for the  $\tau_{cop}$  incentives. In dark blue, the probability is 1, in dark red, the probability is 0.

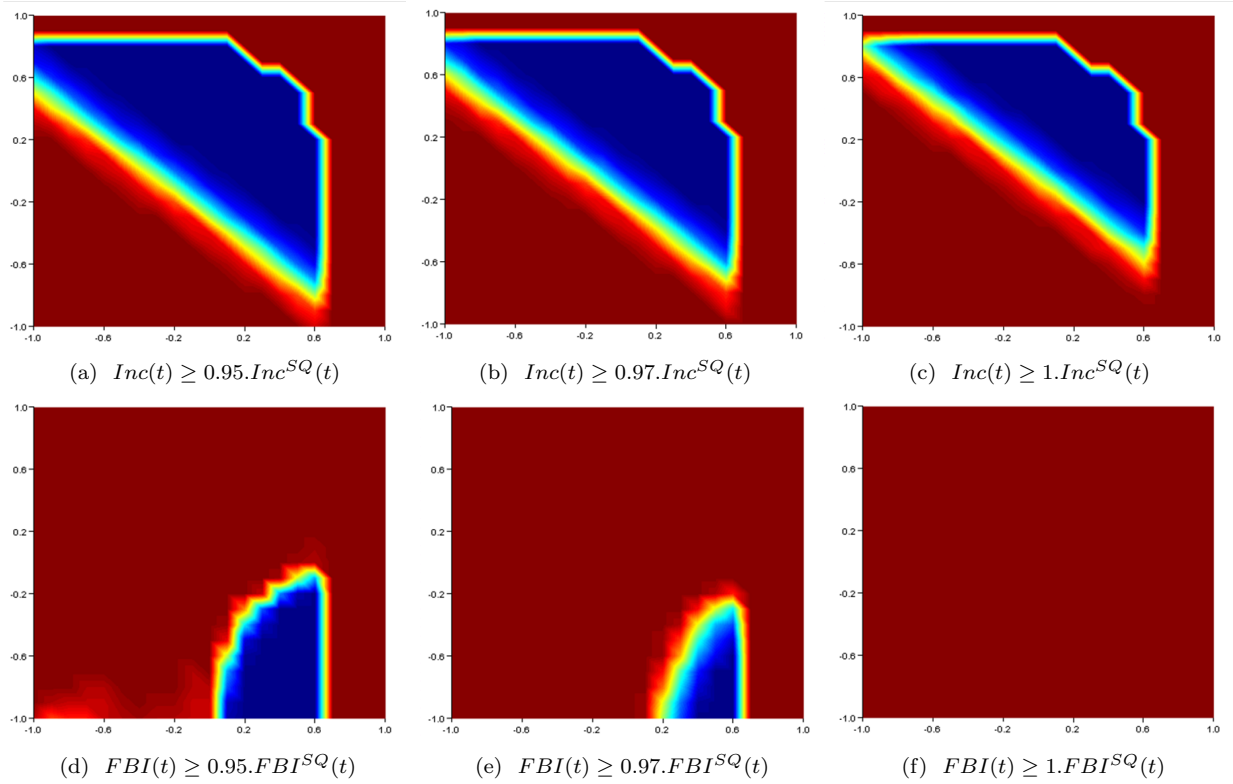


Figure 3: Probability of the different public policies scenarios in an uncertain context to satisfy the set of constraints: the budgetary constraint and an additional constraint which differs according to the graph. The x-axis stands for the  $\tau_{grass}$  incentives and the y-axis for the  $\tau_{cop}$  incentives. In dark blue, the probability is 1, in dark red, the probability is 0.

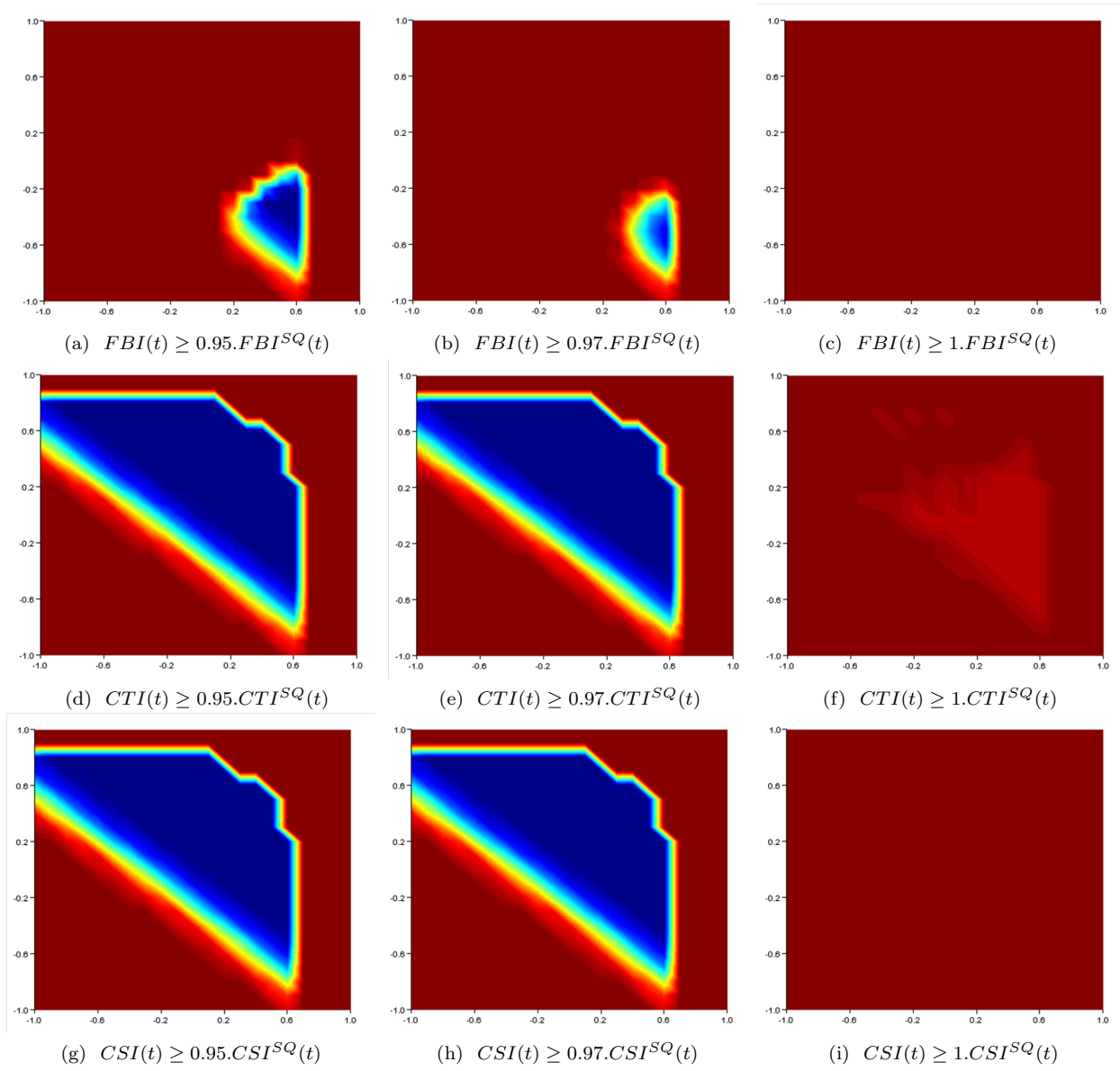
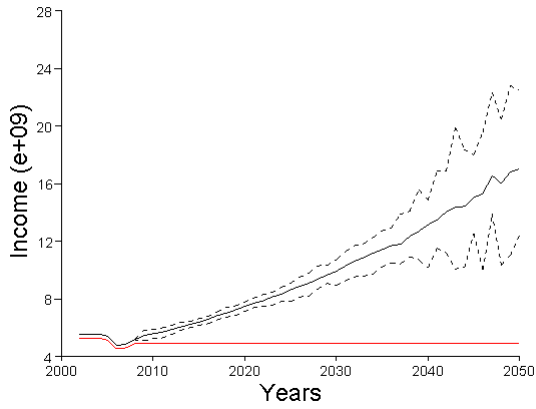
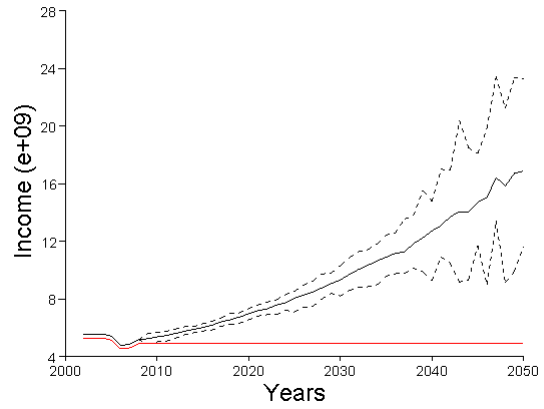


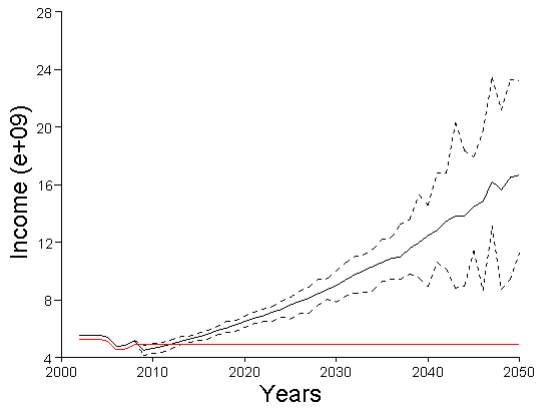
Figure 4: Probability of the different public policies scenarios in an uncertain context to satisfy the set of constraints: the budgetary constraint, the economic constraint  $Inc(t) \geq 0.95.Inc^{SQ}(t)$ , and an additional ecological constraint, which differs according to the graph. The x-axis stands for the  $\tau_{grass}$  incentives and the y-axis for the  $\tau_{cop}$  incentives. In dark blue, the probability is 1, in dark red, the probability is 0.



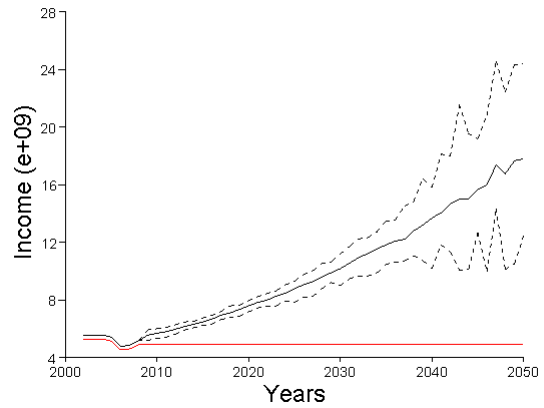
(a)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = 0.7$



(b)  $\tau_{grass} = 0$  and  $\tau_{cop} = 0$



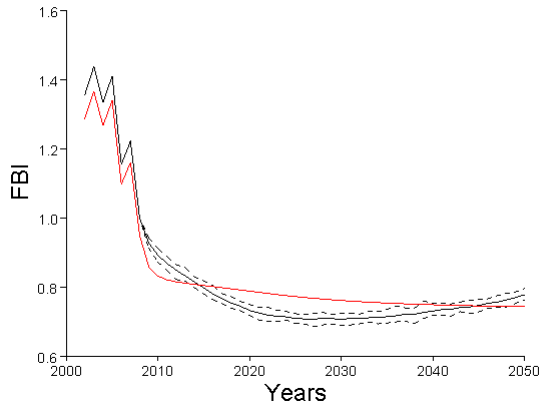
(c)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = -0.2$



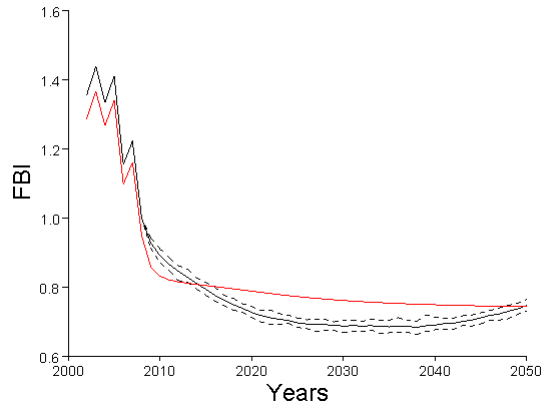
(d)  $\tau_{grass} = 0.6$  and  $\tau_{cop} = -0.2$

Figure 5: Examples of income mean trajectories (black solid lines) and their min and max (black dashed lines) with four public policy scenarios. The red lines represent the constraints with  $\lambda = 0.95$

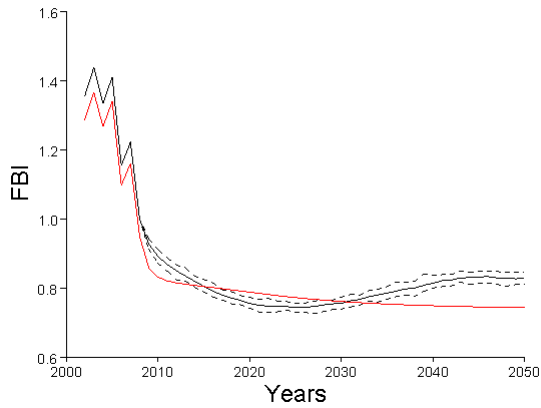




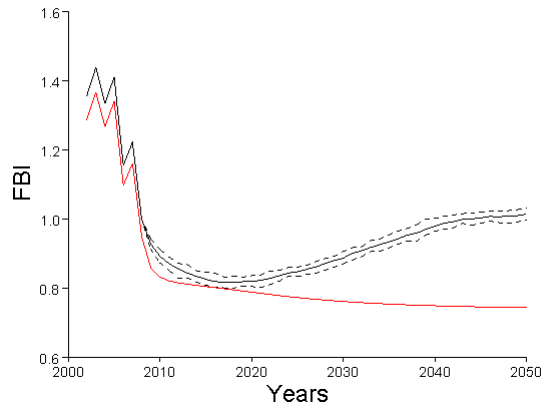
(a)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = 0.7$



(b)  $\tau_{grass} = 0$  and  $\tau_{cop} = 0$

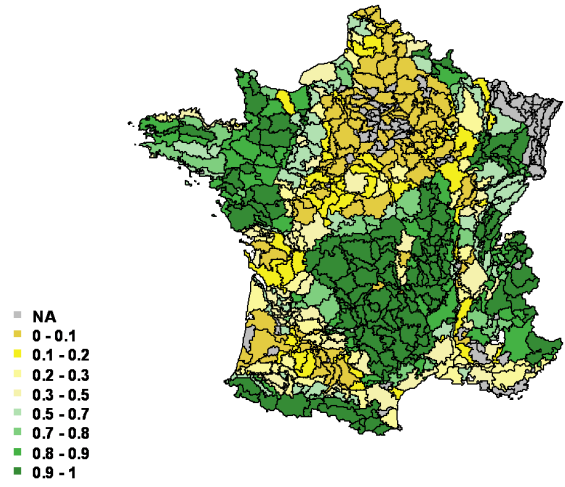


(c)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = -0.2$

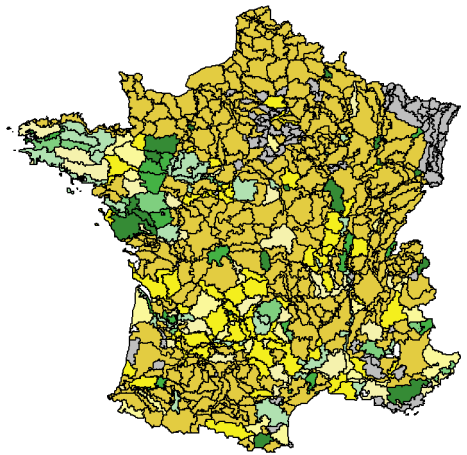


(d)  $\tau_{grass} = 0.6$  and  $\tau_{cop} = -0.2$

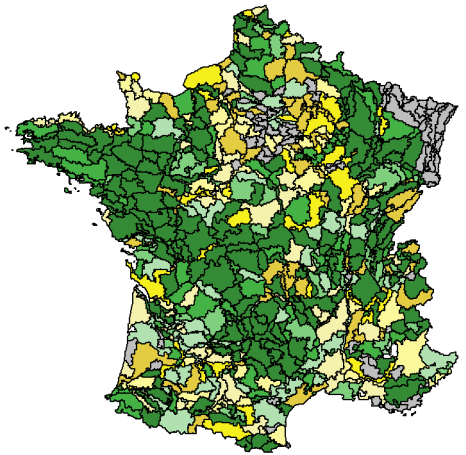
Figure 6: Examples of FBI mean trajectories (black solid lines) and their min and max (black dashed lines) with four public policy scenarios. The red lines represent the constraints with  $\lambda = 0.95$



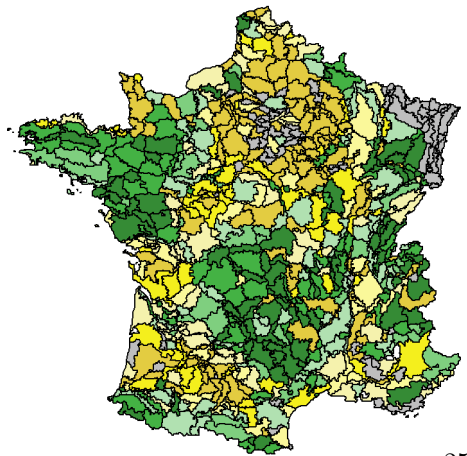
(a) SQ scenario



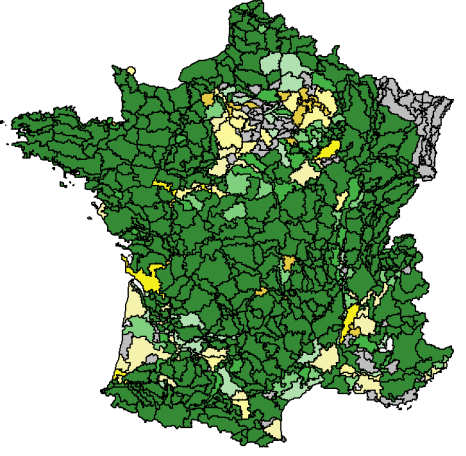
(b)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = 0.7$



(c)  $\tau_{grass} = 0$  and  $\tau_{cop} = 0$



(d)  $\tau_{grass} = -0.6$  and  $\tau_{cop} = -0.2$



(e)  $\tau_{grass} = 0.6$  and  $\tau_{cop} = -0.2$

Figure 7: Proportion of non intensive grasslands of the sum of crops and non intensive grasslands with the Statu Quo scenario (SQ) and four public policy scenarios in 2050.

20 farmland bird species	14 generalist bird species
(1) Buzzard <i>Buteo buteo</i>	(1) Blackbird <i>Turdus merula</i>
(2) Cirl Bunting <i>Emberiza cirlus</i>	(2) Blackcap <i>Sylvia atricapilla</i>
(3) Corn Bunting <i>Emberiza calandra</i>	(3) Blue Tit <i>Parus caeruleus</i>
(4) Grey Partridge <i>Perdix perdix</i>	(4) Carrion crow <i>Corvus corone</i>
(5) Hoopoe <i>Upupa epops</i>	(5) Chaffinch <i>Fringilla coelebs</i>
(6) Kestrel <i>Falco tinnunculus</i>	(6) Cuckoo <i>Cuculus canorus</i>
(7) Lapwing <i>Vanellus vanellus</i>	(7) Dunnock <i>Prunella modularis</i>
(8) Linnet <i>Carduelis cannabina</i>	(8) Great Tit <i>Parus major</i>
(9) Meadow Pipit <i>Anthus pratensis</i>	(9) Green Woodpecker <i>Picus viridis</i>
(10) Quail <i>Coturnix coturnix</i>	(10) Golden oriole <i>Oriolus oriolus</i>
(11) Red-backed Shrike <i>Lanius collurio</i>	(11) Jay <i>Garrulus glandarius</i>
(12) Red-legged Partridge <i>Alectoris rufa</i>	(12) Melodius Warbler <i>Hippolais polyglotta</i>
(13) Rook <i>Corvus frugilegus</i>	(13) Nightingale <i>Luscinia megarhynchos</i>
(14) Skylark <i>Alauda arvensis</i>	(14) Wood Pigeon <i>Columba palumbus</i>
(15) Stonechat <i>Saxicola torquatus</i>	
(16) Whinchat <i>Saxicola rubetra</i>	
(17) Whitethroat <i>Sylvia communis</i>	
(18) Wood Lark <i>Lullula arborea</i>	
(19) Yellowhammer <i>Emberiza citrinella</i>	
(20) Yellow Wagtail <i>Motacilla flava</i>	

Table 1: List of the 20 farmland and 14 generalist bird species *s*

The 14 land-uses (OTEAs)  $k$

---

- (1) Cereal, Oleaginous, Proteaginous (COP)
  - (2) Variegated crops
  - (3) Intensive bovine livestock breeding
  - (4) Medium bovine livestock breeding
  - (5) Extensive bovine livestock breeding
  - (6) Mixed crop-livestock farming with herbivorous direction
  - (7) Other herbivorous livestock breeding
  - (8) Mixed crop-livestock farming with granivorous direction
  - (9) Mixed crop-livestock farming with other direction
  - (10) Granivorous livestock breeding
  - (11) Permanent farming
  - (12) Flower farming
  - (13) Viticulture
  - (14) Others associations
- 

Table 2: List of the 14 farming land-uses (OTEAs)