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A bio-economic analysis for land-uses and biodiversity in metropolitan France

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Une analyse bio-économique pour l'usage des sols et la biodiversité en France métropolitaine

Résumé

L'érosion de la biodiversité est aujourd'hui un enjeu crucial pour la durabilité des écosystèmes. Les activités agricoles et forestières sont parmi les moteurs anthropiques majeurs de ce déclin dans la mesure où des changements d'occupation des sols altèrent les habitats des espèces. Ainsi les politiques publiques agricoles et forestières sont porteuses de réels enjeux en termes de conservation de la biodiversité. Comment concilier objectifs économiques et écologiques au sein ces politiques reste néanmoins un débat ouvert. Dans cette perspective, cet article présente les impacts de scénarios de politiques publiques contrastées en s'appuyant sur un modèle bio-économique dynamique et spatialisé appliqué à la France métropolitaine. Nous mesurons les performances écologiques au travers de 5 indicateurs intégrant les composantes structurelles et fonctionnelles de la biodiversité tandis que les performances économiques sont évaluées via les revenus issus des terres. Nous montrons que des synergies de long-terme entre performances économiques et écologiques peuvent émerger, notamment avec des scénarios d'agriculture extensive. Nos résultats soulignent la nécessité d'adapter les politiques publiques en fonction de l'indicateur de biodiversité. Ces conclusions plaident alors en faveur de l'utilisation de différents indicateurs de biodiversité dans le processus d'élaboration de politique publique.

Mots-clés : Biodiversité, Bio-économie, Usage des sols, Politiques publiques, Scenarios, Climat

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Abstract

Dealing with the erosion of terrestrial biodiversity has become of key importance in order to ensure ecosystems sustainability. Agricultural and forestry activities are one major anthropogenic driver of this decline. The underlying land-use changes result in the alteration of species habitats. Current agricultural and forestry public policies exhibit drawbacks in terms of biodiversity conservation. Reconciling economic and ecological objectives of such public policies thus remains an ongoing critical challenge. In that respect, this paper presents the impacts of contrasted public policy scenarios within a dynamic and spatialized bio-economic framework applied to metropolitan France. We assessed ecological performances through 5 indicators accounting for various structural and functional components of the biodiversity while economic performances refer to land-use incomes. We demonstrate that long-term synergies between ecological and economic performances can emerge, especially within extensive-farming scenarios. Our results underline the necessary adaptation of land-use public policies by taking into account the biodiversity component being supported. We advocate the use of biodiversity indicators into the public decision-making process.

Keywords: Biodiversity, Bio-economics, Land-uses, Public policies, Scenarios, Climate

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1. Introduction

Along with growing anthropogenic pressures on the environment, worldwide evidences of an ongoing severe biodiversity erosion have been recurrently reported in the past decade (Convention on Biological Diversity 2014, Millennium Ecosystem Assessment 2005, World Wildlife Fund 2016). Affecting every taxa, this biodiversity loss is particularly well documented for European common bird populations and related to the intensification of farming and forestry practices (Chamberlain *et al.* 2000, Donald *et al.* 2001, Gregory *et al.* 2007, Robinson *et al.* 1995). One specific driver of such biodiversity loss appears to be the fragmentation of species habitats, defined by Fahrig (2003) as the breaking apart of natural habitats. This fragmentation, along with other environmental degradations linked to human activities (for example soil and water pollution), induces the transformation of species natural breeding and feeding sites (Benton *et al.* 2003, Robinson *et al.* 1995). These ongoing losses and transformations of species habitats alter their nesting success and their access to resources, thus leading to numerous extinctions (Pimm & Raven 2000).

In that respect, considering ecological consequences besides economic objectives within public policies dedicated to land-use is today crucial. Ecological objectives have gradually been integrated into agricultural and forestry public policies. Since 1990, in Europe, the Common Agricultural Policy (i.e. CAP) includes measures such as the Agri-Environmental Schemes (i.e. AES) so as to mitigate the environment degradation (European Commission 2005). Ecological objectives concerning forests have been integrated more lately in public policies, but in 2013, a new European strategy on forests has been adopted and aimed for a common policy framework towards forestry (Commission 2013). This strategy stressed out the importance of taking into consideration forest biodiversity and forest management is today part of the environmental CAP second pillar. However, the ecological efficiency of these environmental-friendly measures remains controversial and has been widely discussed. First, in 2006, Kleijn *et al.* (2006) demonstrated the mixed effect of AES which only show marginal positive effects on common biodiversity in terms of species density. They also pointed out the fact that AES do not exhibit positive impact for endangered species as they only marginally impact the species habitats and resources (Kleijn *et al.* 2006). Then, in 2011, evidences proved that AES could be more efficient if directed towards ecosystemic services (Whittingham 2011). In 2014 finally, Peer *et al.* (2014), warned the community about the weaknesses of the new CAP in terms of biodiversity conservation. The decrease of the CAP second pillar budget, coupled with the possibility to regionally convert up to 5% of grasslands are pointed out to be ineffective drivers for an ecologically efficient agriculture (Peer *et al.* 2014). Designing sustainable public policies thus still remains an ongoing challenge in order to reconcile production objectives with ecological requirements. In this paper, we specifically investigate the issue of including biodiversity objectives into production public policies in order to sustainably manage terrestrial biodiversity.

First, we developed a bio-economic model integrating an ecological model

of bird dynamics coupled with a micro-economic model of land management. Land-use changes over time are used as a proxy for species habitat evolution and allow the coupling of the economic and ecological dynamics. A particular attention has been given to the modeling of ecological dynamics in direct lines with Pereira *et al.* (2010) results, which reaffirmed the need for improved biodiversity models to strengthen the role of scenarios in testing public policies. We thus developed a process-based model of population dynamics explicitly simulating species population growth and extending a former model from Mouysset *et al.* (2011) We additionally modeled the dispersal of individuals through the territory based on metapopulations theory. As climate is considered to be one major driver of biodiversity variations, we also extended the scope of the study by taking into account the species climatic requirements (Jiguet *et al.* 2010, Stephens *et al.* 2016, Thomas *et al.* 2004). Second, we calibrated the whole bio-economic model at the metropolitan France scale by combining ecological data on common breeding birds, economic and land-use data on agricultural and forestry areas and climatic data. Finally, we assessed the economic and ecological performances over time. In that respect, we described the bio-economic dynamics with quantitative economic and non-monetary ecological indicators at national scale.

The paper is organized as follows: sections 2 and 3 present the bio-economic model and the case study. Section 4 presents the bio-economic scenarios. Section 5 presents the results and section 6 is devoted to the discussion.

2. The bio-economic model

The bio-economic model relies on the framework depicted on Fig. 1 and linking the ecological and economic dynamics through the land-uses. A spatially explicit approach is considered: the national territory is split into regions with different environmental characteristics (land cover and climate), biological states (bird abundances) and economic characteristics (unitary profit of each land-use).

2.1. The micro-economic model

At the micro scale, it is assumed that land-uses in region r are managed by a representative land-owner. Each year, the rational regional economic agent determines the surfaces $S_{r,l}$ dedicated to each land-use l by maximizing the regional profit (Eq. 1) under a land availability constraint (Eq. 2) and a rigidity one (Eq. 3). The maximization program in region r thus writes as follows:

$$\max_{S_{r,l}(t)} \Pi_r(t) = \sum_l S_{r,l}(t) [\pi_{r,l}(t) + \delta_l] \quad (1)$$

$$\sum_l S_{r,l}(t) = S_r \quad (2)$$

$$|S_{r,l}(t+1) - S_{r,l}(t)| \leq \xi_l S_{r,l}(t) \quad (3)$$

The regional profit $\Pi_r(t)$ depends on the regional area $S_{r,l}(t)$ dedicated to each land-use l , the related profit per hectare $\pi_{r,l}(t)$ and the potential national public incentive δ_l . A tax is characterized by $\delta_l < 0$ and a subsidy by $\delta_l > 0$. The land availability constraint (Eq. 2) ensures a constant regional surface over time. The rigidity constraint (Eq. 3) limits the amplitude of land-use changes at each period and indirectly takes into account both transition costs between two land-use types and technical issues.

2.2. The ecological model

To model biodiversity dynamics, we developed a spatialized metapopulation model. A metapopulation is defined as a network of interconnected sub-populations (Hanski 1998). Each region r is characterized by one sub-population. This metapopulation dynamics can be split into two steps: first, the reproduction of individuals and second, their dispersal between the regions.

The intra-regional population dynamic is modelled with a Verhulst model (Verhulst 1845) describing a logistic growth such as (Eq. 4):

$$N_{i,r}(t+1) = N_{i,r}(t) \left[1 + r_i - r_i \frac{N_{i,r}(t)}{K_{i,r}(t)} \right] \quad (4)$$

where $N_{i,r}(t)$ is the abundance of species i in region r at time t . The parameter r_i stands for the intrinsic growth rate of species i and is constant for each species at national scale. The variable $K_{i,r}(t)$ represents the carrying capacity of the region r at time t for the species i . The carrying capacity corresponds to the long-term population size of species i . We consider here that the carrying capacity explicitly depends on additive effects of land-use and climate variables as follows (Eq. 5):

$$\frac{1}{K_{i,r}(t)} = a_{i,r}^0 + \sum_l b_{i,l} S_{r,l}(t) + \sum_j c_{i,j} C_{r,j}(t) \quad (5)$$

where $C_{r,j}(t)$ stands for the climatic variable j in region r . The parameter $a_{i,r}^0$ captures a fixed regional effect. This term implicitly describes non-included environmental effects such as the proximity to the coast or the elevation. The parameters $b_{i,l}$ and $c_{i,j}$ represent the response of the species i to the land-use and climatic variables respectively. As environmental conditions $S_{r,l}(t)$ and $C_{r,l}(t)$ vary with time, Eq. 5 implies that the carrying capacities is dynamic.

After the intra-regional dynamics, an inter-regional dynamic occurs between connected regions within the spatial framework. A connection between 2 regions allows the dispersal of individuals between those, according to a national species-specific dispersion rate τ_i . We assumed the dispersal between 2 connected regions to be symmetric.

3. Case study and calibration

3.1. Data

This bio-economic framework has been applied over metropolitan France in $R = 703$ Small Agricultural Regions (i.e. SAR), defined as the intersection be-

tween administrative departments and agricultural regions. One SAR describes an consistent area in terms of agriculture and biodiversity and is thus coherent from an agroecological viewpoint. When the distance between two SAR was inferior to 30 kilometers, we considered the 2 regions to be connected which allows individual dispersal to occur.

The European Corine Land Cover project provided land-use data of metropolitan France in 2000, 2006 and 2012 at the township scale (European Environment Agency 2009). We aggregated the 44 Corine Land Cover land-use types into 6 relevant land-use classes: urban area, annual crops, perennial crops, grasslands, deciduous forests and coniferous forests. We combined various sources to obtain economic data. For land-uses insuring market-good productions (annual crops, perennial crops, deciduous forests and coniferous forests), we used annual regional data produced by the office of statistics and forecasting from the French Ministry of Agriculture. For grasslands, we used extrapolated data from the European Farm Accountancy Data Network. The rigidity parameters ξ_l (see in Eq. 3) have been set with historical data. Economic data are summarized in Tab.?? in App. 1). Based on the ratios between land-use changes and related profits, we fixed the parameters ξ_l in order to ensure a realistic but flexible system (see Tab. 2 in App. 2). Urban and perennial crops areas are supposed stable over time.

We used common birds as the biodiversity metric as they (i) are well identified by the citizens as a biodiversity indicator, (ii) have a high position in the food chain and thus a property to integrate changes occurring in the whole chain, (iii) provide ecosystemic services (Mouysset *et al.* 2013, Sekercioglu *et al.* 2008, Whelan *et al.* 2008). Moreover, evidences report that birds are strongly impacted by farming and forestry evolutions (Chamberlain *et al.* 2000, Donald *et al.* 2001, Ormerod & Watkinson 2000). The French National Museum of Natural History provided the bird abundances over the time series 2002-2014 from the French Breeding Bird Survey (i.e. FBBS) database based on framed naturalistic surveys. This FBBS is a standardized monitoring scheme in which skilled volunteer ornithologist indentify and count breeding bird by song or visual contact twice a year at the same place during several years (Jiguet *et al.* 2012). We studied a wide pool of 60 French common breeding species belonging to 3 different groups based on their habitat preferances (Julliard *et al.* 2006): 14 generalist species, 23 farmland specialist species and 23 woodland specialist species (see Tabs 3, 4 and 5 in App. 3).

The French Ministry of Environment, Energy and See provided climatic data over a time series from 2000 to 2012. Climate effects were described by two variables: the annual average temperature, and the annual average rainfall.

3.2. Calibration

We calibrated the ecological model over a timeline running from $t_0 = 2002$ to $T = 2012$ (Eq. 6). According to the ecological model, bird abundances are thus described by 2 climatic drivers and 6 land-use classes (Eqs. 4 and 5). We performed a linear regression based on the least-squares method on the R-software (using the `lm` function) and estimated the model coefficients for each

species i .

$$LM [N_{i,r}(t+1) \sim \tau_{i,rr} N_{i,r}(t) f_{i,r}(t) + \sum_{\tilde{r} \neq r} \tau_{i,r\tilde{r}} N_{i,\tilde{r}}(t) f_{i,\tilde{r}}(t)] \quad \forall t \in [t_0 : T] \quad (6)$$

where $N_{i,r}(t+1)$ is defined in Eq. 4, $f_{i,r}(t)$ stands for the dynamic described above with Eqs. 4 and 5. The parameter $\tau_{i,r\tilde{r}}$ stands for the dispersal rate τ_i between two connected regions r and \tilde{r} . The function f is specified as follows:

$$f_{i,r}(t) = 1 + r_i - r_i N_{i,r}(t) \left[a_{i,r}^0 + \sum_l b_{i,l} S_{r,l}(t) + \sum_j c_{i,j} C_{r,j}(t) \right] \quad (7)$$

where r_i stands for the growth rate of species i , $N_{i,r}(t)$ stands for the abundance of species i in region r at time t . The parameter $a_{i,r}^0$ captures a fixed regional effect. The parameters $b_{i,l}$ and $c_{i,j}$ represent the response of the species i to the land-use and climatic variables respectively.

Models coefficient of determination (i.e. R2) of the 60 species are reported in Tabs. 3, 4 and 5 in App. 3. The average R2 is of 0.302 + / - 0.165. To further study projected public policy scenarios, we kept the 51 species showing a $R2 > 0.10$. Over the 60 species, 50.30% of the model variable coefficients are significant with a p-value < 0.05 . Fig. 2 illustrates the temporal dynamics of historical and estimated abundances for one species of each group.

4. Scenarios and Indicators

4.1. Public policy scenarios

We tested five national public policy scenarios over a 38-years forecast timeline running from 2012 to 2050. In this work, we investigated contrasted public policy scenarios based on economic incentives.

- The Laissez-Faire scenario (i.e. *LF*) corresponds to the case with none additional public policy ($\delta_l = 0 \forall l$). We can note that it implicitly integrates public policies already existing in 2012 through the regional unitary profits.
- The Business As Usual scenario (i.e. *BAU*) corresponds to the case with new public policies built on the model of the current CAP agri-environmental schemes added: a subsidy on grasslands (i.e. gl) $\delta_{gl} = 200 \text{ euros/ha}$, a subsidy on coniferous forests (i.e. cf) $\delta_{cf} = 200 \text{ euros/ha}$, a subsidy on broadleaves forests (i.e. bl) $\delta_{bl} = 200 \text{ euros/ha}$ and a subsidy on annual crops (i.e. ac) $\delta_{ac} = 600 \text{ euros/ha}$.
- The Intensive Farming scenario (i.e. *IF*) corresponds to the case where objectives of intensive production are reinforced. The cultivation of annual crops is supported by a higher public subsidy $\delta_{ac} = 1000 \text{ euros/ha}$. The other public incentives remain as described in the BAU scenario.

- The Green Farming scenario (i.e. *GF*) corresponds to the case where efforts are made to encourage environmental-friendly practices. The extensification via the maintenance of grasslands is supported by a subsidy $\delta_{gl} = 1000 \text{ euros/ha}$. The other public incentives remain as described in the BAU scenario.
- The Forestry Development scenario (i.e. *FD*) corresponds to the case encouraging the development of forestry over the territory. A public subsidy towards forest areas is set: $\delta_{bl} = 1000 \text{ euros/ha}$ and $\delta_{cf} = 1000 \text{ euros/ha}$. To encourage the conversion of agricultural lands to forest, farming activities are taxed: $\delta_{ac} = -1500 \text{ euros/ha}$ and $\delta_{gl} = -1500 \text{ euros/ha}$.

Those land-use scenarios are run within the same climatic scenario: a climatic Status-Quo scenario where the climatic variables are kept into their 2012 values. This framework makes possible to specifically study the impact of land-use changes into an explicit climatic context since climatic variables are explicitly taken into account in the biodiversity dynamics.

Land-use changes from these land-use scenarios are summarized in Fig. 3. According to our expectations, the scenarios lead to contrasted land-use patterns in 2050. The LF scenario and intensive farming scenarios (i.e. the BAU and IF scenarios) induce a large increase of annual crops areas simultaneously to the decrease of forest and grasslands areas. Extensive farming scenario (i.e. the GF scenario) shows an increase of grasslands and annual crops areas occurring at the expense of forest ones. In the forest scenario (i.e. the FD scenario), forest areas develop whereas grasslands areas decrease and annual crops areas remain stable.

4.2. Bio-economic performances

We investigated different ecological and economic indicators to assess the bio-economic performances over time.

Economic indicators

The economic situation is assessed through the private profits computed yearly at national scale as in Eq. 8.

$$\Pi_{Nat}(t) = \sum_r \sum_l S_{r,l}(t) [\pi_{r,l}(t) + \delta_l] \quad (8)$$

Biodiversity indicators

To assess the ecological performances, we combined two complementary types of ecological indicators, describing the dynamic and the structure of bird communities.

First, we computed for each of the 3 species groups the official European Bird Indicator as defined by Balmford *et al.* (2005) Based on a geometric mean of growth rates, this multi-species indicator describes community dynamics. We computed it as follows for the $F = 17$ farmland specialist (Eqs. 9 and 10), the

$G = 14$ generalist species (Eqs. 9 and 11) and the $W = 21$ woodland specialist (Eqs. 9 and 12) with:

$$N_{i,Nat}(t) = \sum_r N_{i,r}(t) \quad (9)$$

where the variable $N_{i,Nat}(t)$ represents the national abundance of species i at time t .

The national Farmland Bird Indicator (i.e. FBI):

$$FBI_{Nat}(t) = \prod_{i=1}^F \left(\frac{N_{i,Nat}(t)}{N_{i,Nat}(t_0)} \right)^{\frac{1}{F}} \quad (10)$$

The national Generalist Bird Indicator (i.e. GBI):

$$GBI_{Nat}(t) = \prod_{i=1}^G \left(\frac{N_{i,Nat}(t)}{N_{i,Nat}(t_0)} \right)^{\frac{1}{G}} \quad (11)$$

The national Woodland Bird Indicator (i.e. WBI):

$$WBI_{Nat}(t) = \prod_{i=1}^W \left(\frac{N_{i,Nat}(t)}{N_{i,Nat}(t_0)} \right)^{\frac{1}{W}} \quad (12)$$

where t_0 is the year of reference (here $t_0 = 2002$).

Second, we computed two structural indicators assessing the functional state of the community (i.e. the Community Trophic Indicator and the Community Specialisation Indicator) with:

$$N_{tot,r}(t) = \sum_i N_{i,r}(t) \quad (13)$$

where $N_{tot,r}(t)$ stands for the number of individuals in region r at time t .

The national Community Trophic Indicator (Eq. 15) describes the community trophic level and is computed as an average of species abundances weighted by the species trophic index (see Tabs 3, 4 and 5 in App. 3). This specific trophic index informs on each species position in the trophic chain and is based on diets informations as in Julliard *et al.* (2006).

$$CTI_r(t) = \sum_i \frac{N_{i,r}(t)}{N_{tot,r}(t)} STI_i \quad (14)$$

where the parameter STI_i represents the Species Trophic Index of the species i (Julliard *et al.* 2006).

$$CTI_{Nat}(t) = \frac{1}{R} \sum_{r=1}^R CTI_r(t) \quad (15)$$

The Community Specialisation Indicator (Eq. 17) assesses the community specialisation towards specific habitats. Similarly to the CTI, the CSI is computed as a weighted average of species abundances with each species specialisation index (see Tabs 3, 4 and 5 in App. 3). This specific index is computed based on the species habitat preferences as in Julliard *et al.* (2006).

$$CSI_r(t) = \sum_i \frac{N_{i,r}(t)}{N_{tot,r}(t)} \exp(SSi_i) \quad (16)$$

where the parameter $\exp(SSi_i)$ represents the Species Specialisation Index of the species i (Julliard *et al.* 2006).

$$CSI_{Nat}(t) = \frac{1}{R} \sum_{r=1}^R CSI_r(t) \quad (17)$$

5. Results

5.1. Ecological performances of public policy scenarios

Based on the 5 ecological indicators, we analyze the impacts of the 5 public policy scenarios on the biodiversity. The Fig. 4 depicts the relative impacts of the public policies scenarios on bird community sizes. It highlights the difference between farming public policy scenarios and forestry ones. We observe that farming public policy scenarios (i.e. the BAU, the IF and the GF scenarios) positively impact the generalist and farmland specialist species. On the contrary, they have deleterious effects on the woodland specialist species. Forestry scenarios (i.e. the FD scenario) induce positive responses in each species groups (i.e. generalist, farmland specialist and woodland specialist species).

Moreover, Fig. 4 highlights the stronger positive answer of the generalist group compared to the specialist ones for each scenario. This underlines that for all scenarios the communities become less specialized as shown by the evolution of the Community Specialisation Indicator (i.e. CSI) in Fig. 5(a). The Fig. 5(b) describes the relative impacts of each public policy on the community trophic level. Here again we observe the opposition between farming or forestry public policies. Farming scenarios (i.e. the BAU, IF and GF scenarios) induce a community with a slightly higher trophic index than in the LF scenario. This slight increase is due to the specific development of the farmland specialist species with medium trophic level in these scenarios (Fig. 4(b)).

On the contrary, the forestry scenario yields a sharp relative decrease of the community trophic level (Fig. 5(b)). This result looks counter intuitive as woodland species have in average a higher trophic index than others (6.085 for the woodland specialist species against 5.788 for the farmland specialist and 5.634 for the generalist species). We showed on Fig. 6 that the evolution of Community Trophic Indicator (i.e. CTI) in the FD scenario is driven by generalist species: an important development of generalist species in particular with lower trophic index. As a consequence, forestry scenarios induce wider effects on the biodiversity community structure than farming ones.

The general impact of the 5 scenarios on the bird community is summarized in Fig. 7. We show that the ranking of the scenarios in terms of ecological performances changes according to the biodiversity indicator. None scenario exhibits the best performances for all the indicators. We can note that intensive farming scenarios (i.e. as in the BAU and IF scenarios) perform better considering functional indicators (i.e. the CTI and the CSI). On the contrary, forestry-oriented public policies (as in the FD scenario) yield better ecological performances considering community size indicators (i.e. the GBI, the FBI and the WBI). Extensive farming-oriented policy aiming at the development of grasslands (as in the GF scenario) induces intermediate results.

5.2. Underlying bio-economic trade-offs

We combined the impacts of public policy scenarios on biodiversity with economic performances in order to adopt a bio-economic perspective. From an economic point of view, we focused on the private profits. From an ecological point of view, we focused here on the official European indicator: the Farmland Bird Indicator. As depicted on Fig. 8(a), a short-term analysis (i.e. the first 5 years of simulations) does not discriminate the scenarios on ecological bases. Indeed, the FBI decreases with the same amplitude in each scenario during the first years of simulation. This residual decrease is not driven by politically induced land-use change but due to the inertia of ecological dynamics.

The second period between 2020 and 2050 exhibits more contrasted patterns (Fig. 8(b)) and discriminates farming and forestry-oriented public policies. In terms of FBI performances, farming scenarios (i.e. the BAU, IF and GF scenarios) yield better ecological performances with an inversion of the FBI trend in the long-term. The best public policy scenario considering the FBI evolution is the extensive GF one. Intermediate performances are reached with forestry-oriented public policies. The LF scenario is the less effective as it does not exhibit an inversion of the FBI decreasing trend in the long-term. Farming-oriented public policies also yield better economic performances notably compared to the FD scenario.

Finally, the Fig. 9 depicts the long-term bio-economic trade-off. First, this figure highlights the general positive effect of land-use public policies on the biodiversity as the LF scenario with no public policy implemented yields the lower long-term ecological performances. Fig. 9 also highlights a potential synergy between profits and the biodiversity at the long-term. Indeed, the most economically efficient scenarios proves also to be the most ecologically efficient one: the GF scenario thus insures in the long term the best profits and the best ecological performances. We can note that relatively close scenarios in terms of economic results (i.e. the BAU, IF and GF scenarios) yield contrasted ecological performances since the land-use promoted are different.

6. Discussion

6.1. Bio-economic scenarios for the design of sustainable public policies

The first contribution of this paper deals with the bio-economic outcomes of the scenarios investigated. Our results complement knowledge about the long-term trade-off between productive activities and biodiversity in terrestrial ecosystems. We demonstrate a long-term bio-economic state that confirms a potential synergy between private profitability and terrestrial biodiversity: adequate public policies, although being costly especially in the mid-term period, are able to improve ecological performances simultaneously to the economic situation (Bullock *et al.* 2006, Mouysset *et al.* 2012, Steffan-Dewenter *et al.* 2007). In that respect, the extensive-farming scenario (i.e. Green Farming Scenario) shows the best performances by maximizing in the long-term both the FBI and the private incomes. This result confirms the overall beneficial impacts of an increase of grasslands areas (Doxa *et al.* 2010, Mouysset 2014). Thus, we can conclude that within a public perspective of maximising the FBI and the private net income in the long-term, extensive-farming public policies supporting grasslands should be favoured.

The specific target of the incentives (i.e. the land-use being targeted) can however be further discussed. Indeed, the choice to support the development of grasslands at the expense of other land-uses, such as in the Green Farming scenario, has other related impacts such as the equity of the public policy. One of these impacts is linked to the intuition that a marginal increase of grassland would likely be more ecologically profitable in a cropped areas than in an already extensive-farming area. Different land-use being targeted implies different farmers being supported but also discrepancies between the regions. Indeed, in France, regions tend to be specialized towards one usage. Cropped areas such as Beauce in France would thus sparsely benefit from grassland targeted subsidies unless these ones are specifically designed to compensate the cost of allocating land to low-profit grasslands at the expense of highly profitable crops (Firbank *et al.* 2013). Evidence from the literature suggests to focus on enhancing the ecological performances of cropped areas in order to improve biodiversity scores more widely (Butler *et al.* 2007). Our work thus connects to the debate of regionalising public policies within that objective.

6.2. Considering several biodiversity indicators into public policies

These previous bio-economic contributions give some theoretical insights on the interactions and potential long-term synergies between economic and ecological dynamics. They can be put in perspective with the running debate on how to effectively integrate biodiversity objectives into public policies, within their design and evaluation processes.

In order to understand the interactions between public policy and biodiversity, we considered here 5 ecological indicators giving insights into various biodiversity components. Public policy scenarios investigated here raise contrasted results depending on the biodiversity component being investigated. In

that respect, we can conclude that the prior choice of the biodiversity component the public policy maker wants to support should lead to set up various specific public policy measures. Hence, farming species are better conserved within the extensive farming scenario whereas woodland and generalist species show better results within the forestry scenario. The community trophic level, accounting for the functional state of the community, is improved within farming scenarios. With these examples, we underline a necessary adaptation of the public policy strategy in order to maximise the results on the biodiversity component being specifically targeted.

In direct line with the former discussion, our results highlight that the choice to rely on one specific indicator for the design and evaluation of public policy is not neutral from an ecological viewpoint. Notably, choosing to rely on population size indicators (i.e. the FBI, the GBI or the WBI) is not impartial as we highlighted that habitat modifications due to land-use change do not only induce growth rate evolutions, but also structural changes in the communities leading to counter-intuitive trends of national indicators. We emphasized the species redistribution occurring within the Forest Development scenario, not visible through an FBI analysis only. This result stands in line with the literature highlighting the limits of the FBI when it comes to taking into account every kind of species or their habitat requirements (Butler *et al.* 2012, Monnet *et al.* 2014, Stjernman *et al.* 2013). These impacts can however not be set aside since they can stress a loss of resilience in the community. In that respect, we confirm the need for the inclusion of multiple biodiversity metrics in addition to the FBI into the design and evaluations of public policies (Mouysset *et al.* 2012).

6.3. Perspectives

This study emphasizes potential interesting developments for further work, in particular considering the use of bio-economic scenarios to study public policies and biodiversity.

The first perspective is related to the other major global driver of the current biodiversity decline: climate change (Thomas *et al.* 2004). In this paper, we investigated one climatic scenario of Status-Quo and as climate is already included in our modeling framework, the development of contrasted climate change scenarios in parallel to public policy ones would thus provide valuable insights into the future of terrestrial biodiversity. The question of the possibility to mitigate global warming through specific land-use targeted public policies could be investigated and put in perspective with the literature (Ay *et al.* 2014, Princé *et al.* 2013). Moreover, the North-shift hypothesis, consisting in a northerly shift of species distribution range due to climate change, could be tested within our spatialized model (Hitch & Leberg 2007, Perry 2005).

The second perspective is related to our results on the long-term trade-off between production and biodiversity objectives. We discussed the opportunity to rely on regionalised public policies in order to take into account the heterogeneity of productive activities between the regions. In that respect, studying the ecological impacts of public policy scenarios built on spatialized incentives

so as to incorporate the heterogeneous costs of the measures would provide interesting insights into the marginal ecological benefits of each land-use in various regions. These regionalised scenarios could also exhibit specific regional biodiversity changes and thus illustrate the need for further ecological analyses at local scale.

Finally, we emphasised in this paper the need for multi-criteria approaches in order to broadly describe the performances of public policy scenario. In addition to the economic and ecological criteria proposed here, studying the impacts of each public policy scenario with adequate ecosystemic services would provide complementary insights on their general performances. Changes in the bird abundances and in the community structure in parallel to changes of the land-cover over time questions the quantity as well as the quality of the ecosystemic services delivered. Investigating the impacts of such public policy scenarios in terms of ecosystemic services (such as the patrimonial value of birds, carbon sequestration or water and soil quality regulation) would provide valuable developments to the running debate on their inclusion into the process of public-decision making (Bateman *et al.* 2013, Goldstein *et al.* 2012, Whittingham 2011). Our framework allows to consider this wide evaluation of public policy scenario performances in terms of ecosystemic services and would give interesting outputs at the metropolitan France scale.

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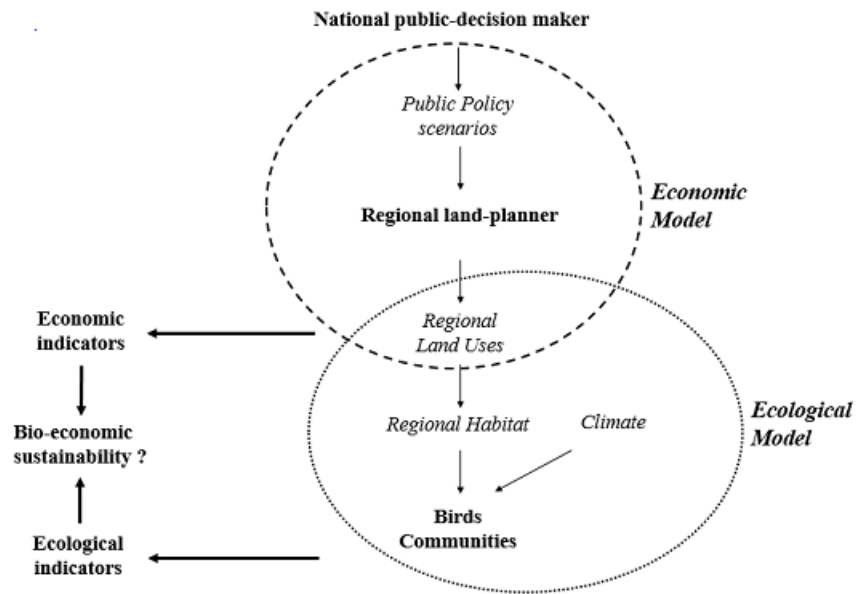
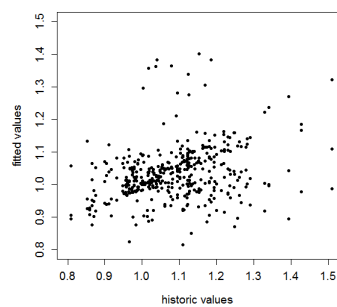
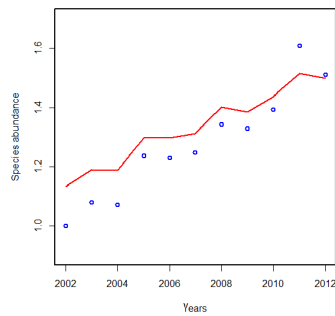


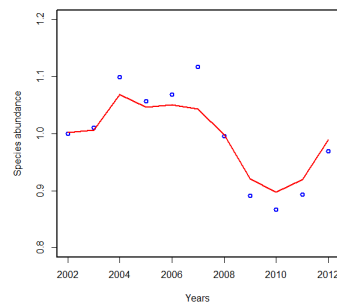
Figure 1: The bio-economic framework.



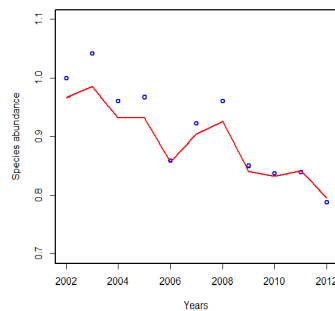
(a) The whole sample of species



(b) Wood pigeon *Columba palumbus*

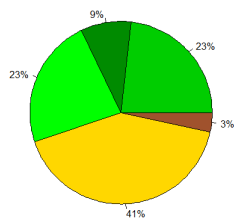


(c) Skylark *Alauda arvensis*

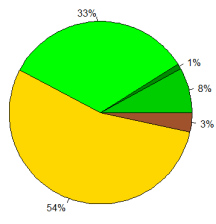


(d) Wren *Troglodytes troglodytes*

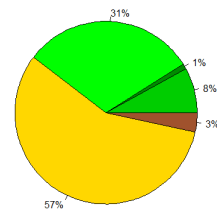
Figure 2: Descriptive performances of the ecological model : Fig. 2(a) compares estimated values to historical ones for the 60 species considered. Example of comparison between historical (points in blue) and estimated (line in red) abundances for 3 species (Fig. 2(b): generalist, Fig. 2(c): farmland specialist and Fig. 2(d): woodland specialist). Abundances are normalized by the 2002 historical value.



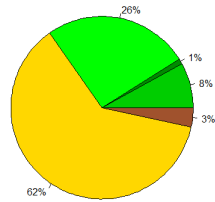
(a) 2012: Initial State



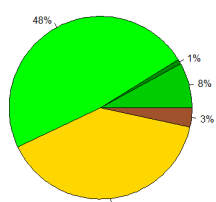
(b) 2050: Laissez-Faire



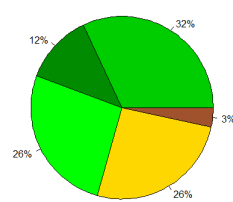
(c) 2050: Business As Usual



(d) 2050: Intensive Farming

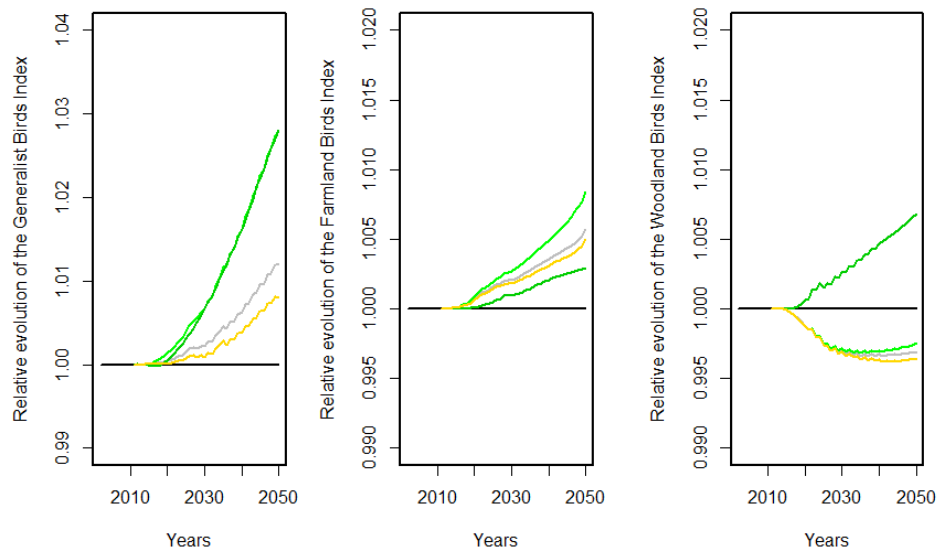


(e) 2050: Green Farming



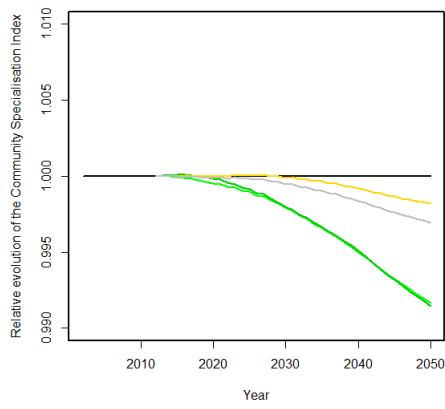
(f) 2050: Forest Development

Figure 3: National land-use patterns in the 5 scenarios. Land-use are labelled as follows: brown = Perennial Crops, yellow = Annual Crops, light green = Grasslands, green = Broadleaves Forests, dark green = Coniferous Forests

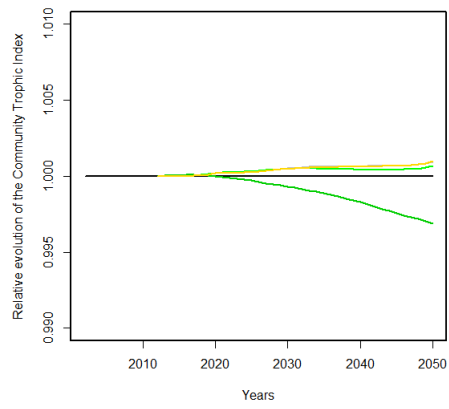


(a) Generalist Bird Indicator (b) Farmland Bird Indicator (c) Woodland Bird Indicator

Figure 4: Marginal temporal evolutions of population indicators in comparison with the Laissez-Faire scenario. Scenarios are labelled as follows: black = Laissez-Faire, grey = Business As Usual, yellow = Intensive Farming, light green = Green Farming, dark green = Forestry Development



(a) Community Specialisation Indicator



(b) Community Trophic Indicator

Figure 5: Temporal evolutions of the Community Specialisation and Trophic Indicators relatively to the Laissez-Faire performances. Scenarios are labelled as follows: black = Laissez-Faire, grey = Business As Usual, yellow = Intensive Farming, light green = Green Farming, dark green = Forestry Development

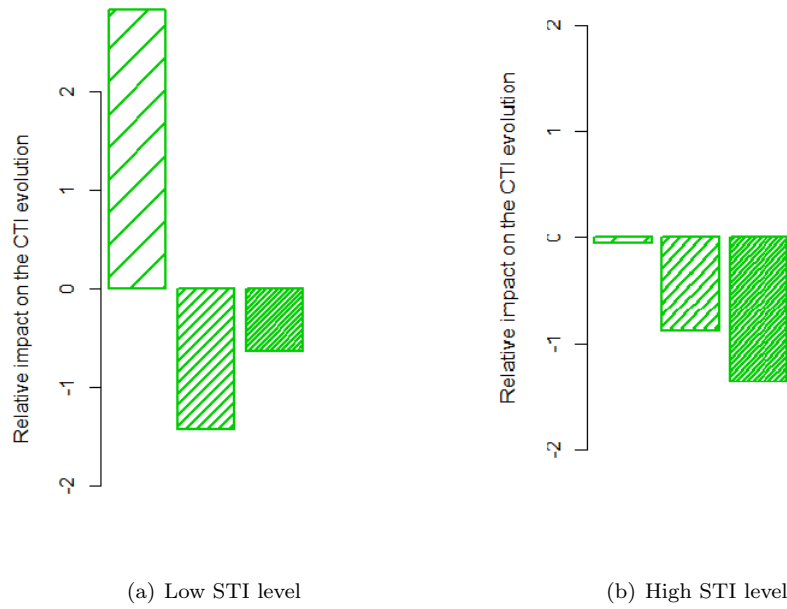


Figure 6: Relative impact of the 3 species groups on the evolution of the Community Trophic Indicator in the FD scenario and function of the species trophic level. Species groups (from left to right): Generalist, Farmland specialist, Woodland specialist.

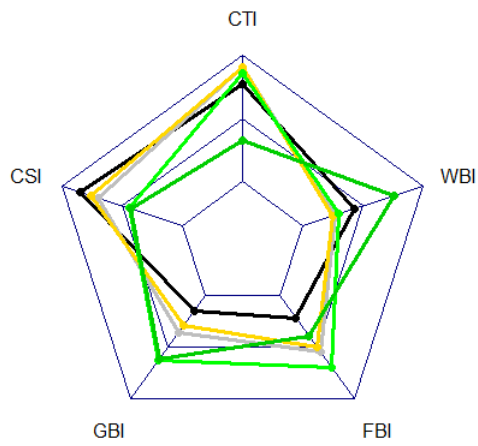
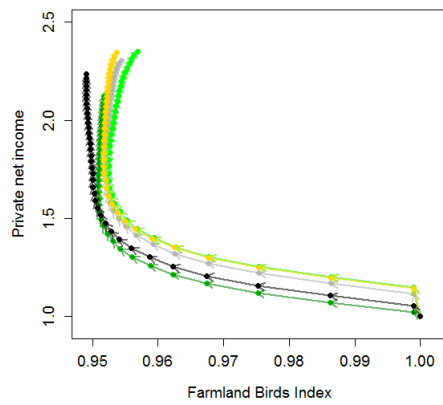
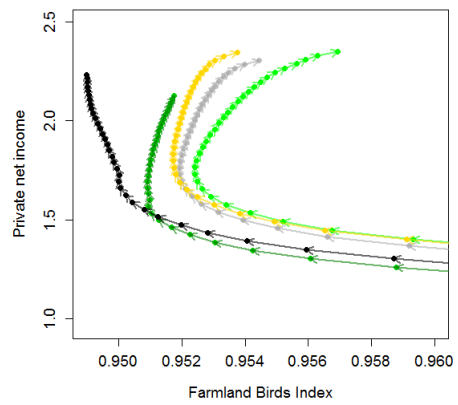


Figure 7: Ecological performances of the 5 public policy scenarios in 2050. Biodiversity indicators are labelled as follows: CSI = Community Specialisation Indicator, CTI = Community Trophic Indicator, GBI, FBI and WBI = Generalist, Farmland and Woodland Bird Indicators. Scenarios are labelled as follows: black = Laissez-Faire, grey = Business As Usual, Light green = Green Farming, Gold = Intensive farming, Dark green = Forest development.



(a) FBI vs Profits: 2012 - 2050



(b) FBI vs Profits: 2020 - 2050

Figure 8: Temporal bio-economic performances of the 5 public policy scenarios. Scenarios are labelled as follows: black = Laissez-Faire Scenario, grey = Business As Usual Scenario, yellow = Intensive Farming Scenario, light green = Green Farming Scenario, dark green = Forestry Development Scenario. The arrow indicates the sense of the temporal dynamic.

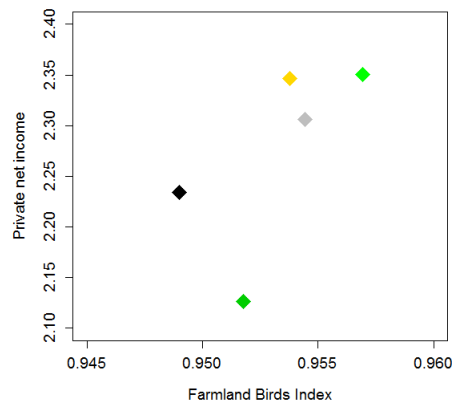


Figure 9: Long-term bio-economic trade-off in 2050: $FBI_{Nat}(2050)$ and $\Pi_{Nat}(2050)$. Scenarios are labelled as follows: black = Laissez-Faire Scenario, grey = Business As Usual Scenario, yellow = Intensive Farming Scenario, light green = Green Farming Scenario, dark green = Forestry Development Scenario

Appendix 1 : Economic data

	Annual crops	Grasslands	Perennial crops	Coniferous forets	Broadleaves forests
Mean (euros/ha)	5992.997	4047.529	42391.734	224,190	119,764
Minimum (euros/ha)	331,293	0.164	30.670	0.315	0.105
Maximum (euros/ha)	939640.454	224804.889	6330000	4053.797	6068.733
Standard deviation	39621.656	10358.904	358544.918	243.072	483.673

Table 1: Summarizing table of economic data

Appendix 2 : Set of the rigidity parameters.

ξ_{bl}	ξ_{cf}	ξ_{ac}	ξ_{gl}	ξ_{pc}	ξ_{urb}
0.03	0.08	0.15	0.06	0	0

Table 2: Set of ξ_l . Land-uses are labelled as follows in the entire paper: bl = Broadleaves, cf = Conifers, ac = Annual Crops, gl = Grasslands, pc = Perennial Crops, urb = Urban

Appendix 3: The species of the study and their characteristics

Species	STI	SSI	R2
Wood Pigeon <i>Columba palumbus</i>	2.746	0.300	0.508
Carrion Crow <i>Corvus corone</i>	4.527	0.281	0.352
Cuckoo <i>Cuculus canorus</i>	7.389	0.043	0.499
Chaffinch <i>Fringilla coloebs</i>	3.004	0.272	0.507
Jay <i>Garulus glandarius</i>	5.585	0.444	0.296
Melodious Warbler <i>Hippolais polyglotta</i>	7.029	0.700	0.288
Nightingale <i>Luscinia megarhynchos</i>	7.389	0.470	0.655
Golden Oriole <i>Oriolus oriolus</i>	7.029	0.473	0.284
Eurasian blue Tit <i>Parus caeruleus</i>	6.050	0.351	0.282
Great Tit <i>Parus major</i>	6.360	0.295	0.425
Green Woodpecker <i>Picus viridis</i>	7.389	0.384	0.338
Dunnock <i>Prunella modularis</i>	4.482	0.495	0.414
Blackcap <i>Sylvia atricapilla</i>	4.953	0.316	0.599
Blackbird <i>Turdus merula</i>	4.953	0.234	0.497

Table 3: Generalist species summary table

Species	STI	SSI	R2
Wood Pigeon <i>Columba palumbus</i>	2.746	0.300	0.326
Short tead Treecreeper <i>Certia brichydactyla Brehm</i>	7.389	0.622	0.326
Eurasian treecreeper <i>Certhia familiaris</i>	7.029	1.889	0.036
Hawfinch <i>Coccothraustes coccothraustes</i>	2.858	0.984	0.205
Great spotted woodpecker <i>Dendrocopus major</i>	5.474	0.638	0.369
Middle spotted woodpecker <i>Dendrocopus medius</i>	5.474	1.921	0.242
Black woodpecker <i>Dryocopus martius</i>	7.389	1.235	0.093
European robin <i>Erithacus rubecula</i>	6.234	0.484	0.438
Coal tit <i>Parus ater</i>	4.953	1.386	0.378
European crested tit <i>Parus cristatus</i>	4.953	1.617	0.195
Marsh tit <i>Parus palustris</i>	5.474	0.988	0.161
Western Bonelli's warbler <i>phylloscopus bonelli</i>	7.389	0.859	0.487
Chiffchaff <i>Phylloscopus collybita</i>	7.029	0.460	0.508
Wood warbler <i>Phylloscopus sybillatrix</i>	7.029	1.720	0.276
Willow warbler <i>Phylloscopus troquillus</i>	7.029	1.118	0.458
Grey-headed woodpecker <i>Picus canus gmelin</i>	7.389	1.317	0.125
Bulfinch <i>Pyrrhula pyrrhula</i>	3.004	1.053	0.096
Goldcrest <i>Regulus regulus</i>	7.389	1.081	0.235
Nuthatch <i>Sitta europaea</i>	7.389	1.460	0.328
Sardinian warbler <i>Sylvia melanocephala</i>	5.474	0.756	0.493
Wren <i>Troglodytes troglodytes</i>	7.389	0.372	0.632
Song Trush <i>Turdus philomelos Brehm</i>	4.807	0.402	0.449
Mistle Trush <i>Turdus viscivorus</i>	4.711	0.518	0.249

Table 4: Woodland specialist species summary table

Species	STI	SSI	R2
Wheatears <i>Oenanthe oenanthe</i>	7,030	1,704	0,035
Grey Partridge <i>Pendix pendix</i>	3.004	2.196	0.505
Winchat <i>Saxicola rubetra</i>	7.389	1.463	0.054
Stonechat <i>Saxicola torquata</i>	7.389	0.776	0.101
Whitethroat <i>Sylvia communis Latham</i>	4.953	0.654	0.343
Hoopoe <i>Upupa epops</i>	7.389	0.607	0.185
Lapwing <i>Vanellus vanellus</i>	6.686	2.228	0.090
Skylark <i>Alauda arvensis</i>	3.490	1.155	0.570
Red-legged Partridge <i>Alectoris Rufa</i>	3.004	1.097	0.280
Tawny Pipit <i>Anthus campestris</i>	7.029	1.996	0.213
Meadow Pipit <i>Anthus prathensis</i>	5.755	0.375	0.017
Buzzard <i>Buteo buteo</i>	18.174	0.495	0.151
Linnet <i>Canduelis cannabina</i>	2.858	0.697	0.144
Rook <i>Corvus frugilegus</i>	5.104	0.846	0.209
Quail <i>Coturnix coturnix</i>	3.387	1.524	0.094
Cirl Bunting <i>Emberiza cirrus</i>	3.669	0.586	0.394
Yellow Hammer <i>Emberiza citrinella</i>	3.669	0.711	0.474
Firecrest <i>Regulus ignicapillus</i>	7.389	0.681	0.145
Crested Lark <i>Galerida cristata</i>	4.710	1.711	0.324
Red-backed Shrike <i>Lanius collurio</i>	8.585	1.141	0.076
Wood lark <i>Lullula arborea</i>	4.482	0.903	0.296
Corn Bunting <i>Miliaria callandra</i>	3.597	1.464	0.374
Yellow Wagtail <i>Motacilla flava</i>	7.3	2.091	0.249

Table 5: Farmland specialist species summary table

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