Supplementary Appendix (only online)

A Map of the Aquitaine region

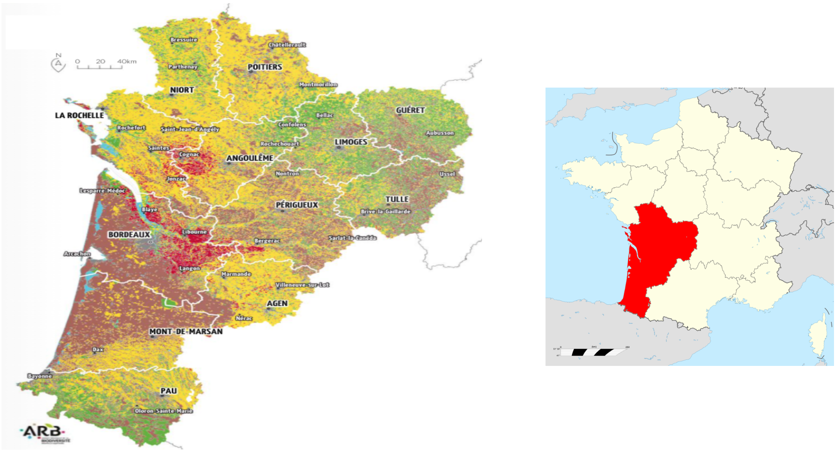


Fig. 6: Maps of the NA region: (left) Land-use 2018 (together with the administrative delineations of departments and the main cities); in red, vineyards; in yellow, croplands; in brown, forests; in green, grasslands; and in grey, urban areas; (Source : © Agence Régionale Biodiversité (ARB) NA - Agence Européenne de l'Environnement - BD Corine Land Cover 2018) ; (right) the NA region (red) as compared to other regions in metropolitan France.

B Details about the modeling framework

B.1 Land-use changes

We gather up to 26 climatic and biophysical variables to model finely the determinants of LUCs and the other outcomes variables described below (i.e., economic returns and bird distribution). These variables are highly correlated between them, which leads to multi-colinearity issues in the statistical estimation of the models. Hence, we perform two Principal Component Analysis in order to reduce the dimension of the raw variables by keeping only the two first axis for each set of variables (Figure 7 in OA shows the relationships between the climate variables and these two principal axes, which account for 87% of the total initial variance).

Data about LUC are extracted from the TERUTI survey which was carried out every year 1992-2003 by the statistical services of the French Ministry of Agriculture. TERUTI data count about 550,000 points for which we know the location in terms of French municipalities. The TERUTI survey uses a systematic area frame sampling with a two-stage sampling design. In the first stage, the total national area is divided into a 12×12 km grid. For each of these 4,700 regular meshes there are 4 aerial photographs which cover 3.5 km^2 each. In the second stage, on each photograph, a 6-by-6 grid determines the 36 points to be surveyed in June by an agent on the ground. Each point corresponds to a homogeneous unit in terms of land use and statistically represents about 100 hectares (ha) at the département scale (n = 95, median area: 5,880 km^2). On the basis of the detailed classification of land uses (81 items) we attribute to each plot a use among 5 more aggregate items: annual crop (wheat, corn, sunflowers, etc.), pasture (a rather large defintion: grassland, rangelands, productive fallows, moor), perennial crop (vineyard, orchard and greenhouses), forest (both productive and recreative, including plantation, hedgerow) or urban (cities and exurban houses but also roads, highways, airports, etc.)

The estimation of LUC models was performed using `nnet 7.3` on `R`. The unobserved factors are assumed to be uncorrelated over alternatives and periods, as well as having a constant variance. These assumptions, used to provide a convenient form for the choice probability, were found to be not restrictive (homoscedasticity cannot be rejected by a score test, p-value= 0.283). Moreover, these hypotheses are associated with the classical restriction of Independence of Irrelevant Alternatives (IIA) for which Hausman-McFadden specification tests are performed, with mixed evidence. The independence is not rejected for three uses: pasture, perennial crop and urban (p-values are respectively 0.001, 0.005 and 0.036) but rejected for annual crop and forest at 5%. In the land use econometric literature, use of nested multinomial logit is found not to change the results.

B.2 Background data

Biophysical attributes of sampled plots include both topographic and climate variables. Topography of each plot was generated by coupling a Digital Elevation Model of France (resolution of 250 meters) with the spatial geo-referencement of plots. Within a Geographical Information System (GIS), we calculated the elevation, the slope, the roughness and the exposition of each TERUTI sampled plot. Soil quality variables were extracted from the French soil database developed by the National Institute for Agricultural Research and matched by GIS. The initial data are available at the 1:1,000,000-scale (Jamagne et al. 1995) and they were downscaled to a 1-km grid with pedotransfert rules (Cheaib et al. 2012). They provide measures of the agricultural fertility of plots: plant available water capacity and soil depth. We use historical (1990–2010) and projected (2010–2053) climate data, both available at the same spatial resolution (8×8 km rasters) with a smooth transition between historical and future climate. Climate data include 13 variables about temperatures (annual means, maximum and minimum, bird breeding period means April–August and seasonality approximated by standard deviation), precipitations (annual means, maximum and minimum, breeding period means and seasonality), solar radiation (breeding period means), relative humidity (breeding period means) and wind (breeding period means). Regionalized climate scenarios are based on the Intergovernmental Panel of CC' SRES A1B greenhouse gas emissions scenario A1B coupled with the Météo-France Arpège climate model (Déqué 2007). Regionalized climate projections were produced with a multivariate statistical downscaling methodology, which is able to generate local time series of temperature and precipitation, and other climatic variables at different sites (Boé et al. 2009). The model is based on large-scale circulation predictors, here the mean sea-level pressure field, as well as the 2-meter temperature averaged over France. It starts from regional climate properties to establish discriminating weather types for the chosen local variable. Intra-type variations of the relevant forcing parameters are then taken into account by multivariate regression using the distances of a given day to the different weather types as predictors. The final step consists of conditional re-sampling (for further details in climate downscaling see Boé et al. 2009 and Cheaib et al. 2012).

B.3 Economic returns

The price of land is used to compute the expected net returns from different agricultural land uses. Defining land price as the net present value of expected future rents is standard in the economic theory (Ricardo 1817; Goodwin et al. 2003). This approach, detailed in the main text, uses data about land prices that also come from the statistical services of the French Ministry of Agriculture. Yearly prices 1990–2005 are available for three land uses (annual crops, pastures and perennial crops) and for the 713 Small Agricultural Regions (SAR) of France. SAR size ranges from 11 to 4,413 km^2 with an homogeneity in terms of both agro-ecological and economic levels, reducing intra-SAR heterogeneity (Mouysset et al. 2012). For the two others considered land uses – forest and urban – the approximations of economic returns are computed differently and at different geographic scales. For the expected net returns from forest, we use data about wood raw production (in m^3), total forest area (in ha) and wood prices (in current euro per ha), all available annually at the scale of the French départements. We compute the expected returns from forest by multiplying the aggregate production by its unitary price and dividing the result by the total forest area of each département. This simplification is based on the assumption of a myopic agent who makes decisions based on the hypothesis that future returns will be the same as today and neglect production costs. The urban returns are approximated by the population densities at the fine scale of the municipalities (number of people per total area) on the basis of the national census of French population. In France, the municipality is the administrative body where development planning choices (constructability, servicing) are operated.

The Ricardian equations are estimated separately for annual crop, pasture, perennial crop and forest using Generalized Additive Models (GAM). The smoothing functions and the penalization parameter have to be estimated jointly, with a distribution from the Gaussian family and a natural logarithm link. For the dynamics of the urban returns, we use the spatialized projections of population growth by the French demographic institute. Because these projections are available at the *département* scale[14], we have downscaled them by assuming that each municipality keeps a constant proportion of the aggregate values. Table 3 in the Appendix shows the detailed results of the calibration for the Ricardian model of economic returns.

B.4 Bird abundances

We used avian data from the French Breeding Bird Survey (FBBS), a standardized monitoring scheme in which skilled volunteer ornithologists identify breeding birds by song or visual contact in spring (Jiguet et al. 2012). In FBBS, each observer provides the name of her municipality, and a 2×2 km square to be prospected is randomly selected within a 10 km radius from the gravity center of this municipality. In each square, the observer monitors 10 point counts separated by at least 300 m twice per spring (4 to 6 weeks between the sessions, 5 minutes each). Counts were repeated yearly by the same observer at the same points, on about the same date (with a maximum difference of 7 days within April to mid June) and at the same time of day (with a maximum difference of 15 minutes). FBBS data contribute to European official index of biodiversity and have been extensively used to study the effects of climate and LUC on bird populations (Barbet-Massin et al. 2011; Barnagaud et al. 2012), as well as the effects of farmers preferences and the effects of agro-environmental policies. To simultaneously smooth annual noise and model the observed dynamics, FBBS data are used at two points of time, 2003 (the average 2002-2004, $n = 1,031$) and 2009 (the average 2008–2010, $n = 1,380$). For each species and each FBBS square, bird abundances are defined as the maximum number of counts. FBBS provides also a description of the habitats of the surveyed squares. The SDM are estimated with FBBS habitats description (with an equivalence

[14] Département is a French administrative division ranging in size from ca. 600 to 10,550 km^2

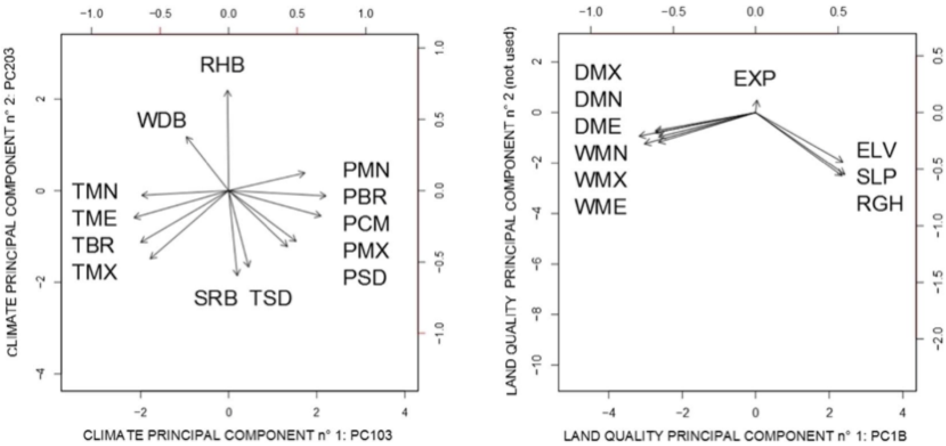
of items to the other land use data to perform predictions) and each FBBS observation is weighted in the regressions according to its significance in terms of local land use. On their own, FBBS habitats description is not representative of the local land use.

To estimate SDM presented in the text, we use the `gam()` function from the `R` package `mgcv 1.7`. Because the impacts of CC on species distributions have been shown to vary depending on choice of modeling technique (Buisson et al. 2010 and Garcia et al. 2012) and of spatial structure (Dormann et al. 2007), we have estimated other SDMs based on alternative assumptions. We also fitted negative binomial mixed models without including geographical coordinates (with the `R` package `glmmADMB`, see Table 2 in the Appendix). Including geographical coordinates increases the goodness-of-fit but have a relative limited impact on abundance variations within scenarios, we focus only on the results from the negative binomial GAMs here for the sake of clarity.

Here again the two principal axes at time t and location q of a Principal Component Analysis of the climatic variables matrix are used to reduce colinearity problems. Figure 7 in OA shows the relationships between the climate variables and these 2 principal axes, which account for 87% of the total variance.

C Additional Figures and Tables

Fig. 7: Principal Component Analysis for climate and land quality variables



Notes: For climate variables (left panel), RHB: mean relative humidity during breeding, WDB: mean wind during breeding, TMN: minimal monthly temperature, TME: mean monthly temperature, TBR: mean temperature during breeding, TMX: maximal monthly temperature, PMN: minimal monthly precipitation, PBR: mean precipitation during breeding, PCM: mean monthly precipitations, PMX: maximal monthly precipitation, PSD: seasonality of precipitations, TSD: seasonality of temperatures, SRB, mean solar radiation during breeding. For land quality (right panel), DMX: maximal soil depth, DMN: minimal soil depth, DME: mean soil depth, WMN: minimal water holding capacity of soils, WMX: maximal water holding capacity, WME: mean water holding capcity, EXP: exposition, ELV: elevation, SLP: slope, RGH: roughness. The two main axis for climate variables are used, only the first for soil variables.

Table 2: Results of Species Distribution Models for the 65 common bird species in the national scale

Generalized Additive Models with Negative Binomial distributions					
N= 65	Min	Q1	Q2	Q3	Max
Adj.$-R^2$	.15	.29	.37	.43	.87
Corr(N,$\widehat{N}$)	.43	.57	.62	.67	.94
Statistical significance of explanatory variables					
VAR	CLIMATE	ANCR	PAST	FORE	URBA
p-value ¡ .01	56/65	52/65	25/65	62/65	52/65
% of species	(86)	(80)	(38)	(95)	(80)

Notes: 65 Species Distribution Models are estimated, one for each bird species of interest. The top panel of the Table presents the distribution of the adjusted R-squares and of the correlations between observed and predicted abundances. The two principal components of climate variables (left panel of Figure ORF1) are included in SDM with bivariate smoothing functions. Land use shares (ANCR for annual crops, PAST for pasture, FORE for forest and URBA for urban, perennial crop is the reference land use) have each their own additive smooth functions. The bottom panel of this Table presents the results about the 1 % statistical significance of each smoothed terms (both bivariate and univariates).

Table 3: Summary of the results from the 4 econometric Ricardian models

	$F-\mathbf{c}_{qt}$	$F-\mathbf{e}_q$	$F-POP$	$F-\mathbf{m}_q$	γ_ℓ	(n,t)	**Adj.**-R^2
ANCR	4.95**	11.6**	29.6**	14.8**	.028**	(713, 3)	.785
PAST	4.13**	11.6**	17.5**	6.11**	.012**	(713, 3)	.766
PECR	3.62**	0.43	2.90*	20.6**	.007*	(93, 2)	.914
FORE	6.46**	1.68	0.65	19.9**	.000	(93, 3)	.361

Notes: Only 4 Ricardian models (in row) are estimated because the proxy for urban returns is predicted from deterministic national projections. ** stands for 0.01% of statistical significance, * for 1%. The table reports the values of F-tests for statistical significance. Climate variables, c_{qt}, enter by their two principal components inside bivariate smoothing functions. Land quality variables, e_q, enter by their first principal component inside univariate smoothing functions. Human population (POP) is also included in these Ricardian models, as spatial coordinates m_q of the centroïds of each Small Agricultural Regions. The latters enter as two arguments of bivariate smoothing functions. The fifth column reports the coefficients for the annual trends and their significance. The table also contains the cross-sectional and temporal dimensions of the data used to estimated Ricardian models. They are principally shaped by data availability: n= 713 where the estimation is at the scale of Small Agricultural Regions and n= 93 for the French départements, see Table ST4. Three of these models are estimated on pooled data from three points of times: 1993, 1998 and 2003. Again because of data limitations, the Ricardian model for perennial crop is estimated on only two periods: 1993 and 1998. The last column contains the adjusted R-squares associated to each model.

Table 4: Robustness results of Species Distribution Models

Mixed Models with Negative Binomial distributions					
N=55	Min	Q1	Q2	Q3	Max
Corr(N,$\widehat{N}$)	.22	.40	.47	.56	.78
Statistical significance of explanatory variables					
VAR	CLIMATE	ANCR	PAST	FORE	URBA
p-value $<$ .01	34/55	37/55	16/55	52/55	39/55
% of species	(62)	(69)	(27)	(95)	(71)

Notes: The number of bird species falls from 65 in the negative binomial GAMs to 55 here because of no convergence of estimation process for 10 species. The random effects are specified at the départements scale, see table ST4. The covariates are specified as polynomials of order 2 (the bottom panel of the Table reports joint statistical significance). The geographical coordinates are not included as covariates, to stress the differences with the other SDMs. In comparison with the results from Table ST1, the predictive abilities are smaller the climate and land use variables are less often significants.

Table 5: The Ricardian effects of CC on the economic returns from land: amounts in current euros and in variations

	2003		**2053**		**Variations 2003-2053**				
Land Use	Mean	SE	Mean	SE	Min	Q1	Q2	Q3	Max
ANCR	265.4	92.27	587.7	346.2	− 100.0	+ 72.05	+ 116.8	+ 159.4	+ 323.5
PAST	113.9	73.35	191.7	103.8	− 24.10	+ 52.62	+ 73.81	+ 98.21	+ 341.7
PECR	177.3	730.1	185.6	699.4	− 75.18	+ 4.474	+ 13.35	+ 19.01	+ 196.0
FORE	80.90	60.07	69.92	53.31	− 44.76	− 16.25	− 13.18	− 8.742	+ 45.36
URBA	81.98	291.8	103.0	386.8	− 29.10	+ 13.99	+ 28.31	+ 46.81	+ 109.4

Notes: The mean values of returns are in current euros/ha for the first 4 rows and hab/km^2 for the last. SE is for standard errors, variations are expressed in %. ANCR counts for annual crops, FORE for forests, PECR for perennial crops, PAST for pastures and URBA for urban

Table 6: Biodiversity conservation scenario BCS with alternative values for pasture payments

BCS biodiversity conservation scenario **with 100 euro/ha**					
	Perennial crops	Annual crops	Pastures	Forests	Urban areas
2003	2968.27	20984.52	25184.69	31320.01	4502.51
2013	3152.78	21163.72	24863.33	31155.26	4624.88
2023	3337.29	21342.93	24541.97	30990.52	4747.26
2033	3521.81	21522.14	24220.62	30825.78	4869.64
2043	3706.32	21701.35	23899.26	30661.03	4992.02
2053	3890.83	21880.55	23577.90	30496.29	5114.40
Δ(%)	31.08	4.27	-6.38	-2.63	13.59

BCS biodiversity conservation scenario **with 300 euro/ha**					
	Perennial crops	Annual crops	Pastures	Forests	Urban areas
2003	2968.27	20984.52	25184.69	31320.01	4502.51
2013	3219.61	21282.08	25005.37	30795.71	4657.21
2023	3470.96	21579.64	24826.06	30271.41	4811.92
2033	3722.30	21877.20	24646.74	29747.11	4966.62
2043	3973.65	22174.76	24467.43	29222.82	5121.33
2053	4224.99	22472.32	24288.11	28698.52	5276.04
Δ(%)	42.33	7.09	-3.56	-8.37	17.18

Table 7: Bird species with their habitat specialization and their specific trophic index

Name	HABITAT	Species	STI
Sky Lark	AGR	*Alauda arvensis*	1,25
Red-legged Partridge	AGR	*Alectoris rufa*	1,1
Common Swift	URB	*Apus apus*	1,75
Common Buzzard	AGR	*Buteo buteo*	2,9
Linnet	AGR	*Carduelis cannabina*	1,05
Goldfinch	URB	*Carduelis carduelis*	1,05
Greenfinch	URB	*Chloris chloris*	1,05
Short-toed Treecreeper	FOR	*Certhia brachydactyla*	
Hawfinch	FOR	*Coccothraustes coccothrauste*	
Wood Pigeon	GEN	*Columba palumbus*	1,01
Carrion Crow	GEN	*Corvus corone*	1,51
Western Jackdaw	URB	*Coloeus monedula*	
Common Quail	AGR	*Coturnix coturnix*	1,22
Common Cuckoo	GEN	*Cuculus canorus*	2
House Martin	URB	*Delichon urbicum*	
Great Spotted Woodpecker	FOR	*Dendrocopos major*	1,21
Black Woodpecker	FOR	*Dryocopus martius*	
Cirl Bunting	AGR	*Emberiza cirlus*	1,3
Yellowhammer	AGR	*Emberiza citrinella*	1,3
Robin	FOR	*rubecula rubecula*	
Common Kestrel	AGR	*tinnunculus rubecula*	2,85
Common Chaffinch	GEN	*Fringilla coelebs*	1,1
Eurasian Jay	GEN	*Garrulus glandarius*	1,72
Melodious Warbler	GEN	*Hippolais polyglotta*	1,95
Barn Swallow	URB	*Hirundo rustica*	
Red-backed Shrike	AGR	*Lanius collurio*	2,15
Wood Lark	AGR	*Lullula arborea*	1,5
Rufous Nightingale	GEN	*Luscinia megarhynchos*	2
Corn Bunting	AGR	*Emberiza calandra*	1,3
Yellow Wagtail	AGR	*Motacilla flava*	2
Golden Oriole	GEN	*Oriolus oriolus*	1,95
Coal Tit	FOR	*Periparus ater*	
Blue Tit	GEN	*Cyanistes caeruleus*	
Crested Tit	FOR	*Lophophanes cristatus*	2
Great Tit	GEN	*Parus major*	1,85
Marsh Tit	FOR	*Poecile palustris*	
House Sparrow	URB	*Passer domesticus*	
Tree Sparrow	URB	*Passer montanus*	
Grey Partridge	AGR	*Perdix perdix*	1,1
Black Redstart	URB	*Phoenicurus ochruros*	
Common Redstart	URB	*Phoenicurus phoenicurus*	
Western Bonelli's Warbler	FOR	*Phylloscopus bonelli*	
Common Chiffchaff	FOR	*Phylloscopus collybita*	
Wood Warbler	FOR	*Phylloscopus sibilatrix*	
Willow Warbler	FOR	*Phylloscopus trochilus*	
Magpie	URB	*Pica pica*	
Green Woodpecker	GEN	*Picus viridis*	2
Dunnock	GEN	*Prunella modularis*	1,5
Bullfinch	FOR	*Pyrrhula pyrrhula*	
Firecrest	FOR	*Regulus ignicapilla*	
Goldcrest	FOR	*Regulus regulus*	
Whinchat	AGR	*Saxicola rubetra*	2
Common Stonechat	AGR	*Saxicola rubicola*	2
European Serin	URB	*Serinus serinus*	
Eurasian Nuthatch	FOR	*Sitta europaea*	
Collared Dove	URB	*Streptopelia decaocto*	
Blackcap	GEN	*Sylvia atricapilla*	1,6
Common Whitethroat	AGR	*Sylvia communis*	1,6
Wren	FOR	*Troglodytes troglodytes*	
Blackbird	GEN	*Turdus merula*	1,6
Song Thrush	FOR	*Turdus philomelos*	1,6
Mistle Thrush	FOR	*Turdus viscivorus*	1,6
Hoopoe	AGR	*Upupa epops*	2

Table 8: Ecosystem scores considered in the study

Outputs	Metrics	Data and method
Biodiversity	Bird abundances index, Shannon index, community specialization index, community trophic index	Bird abundances per TERUTI grid square from Species distribution model (SDM)
Carbon sink intensity	Carbon sink intensity net metric tons per TERUTI grid square assessed for CO2, CH4, CF4,and N20 converted to CO2 equivalent	Carbon sink intensity responses to land use predictions using net tCO2eq/ha/year carbon sink input from French Assessment of Ecosystem and ESs (EFESE 2019)
Water quality	Inverse of Nitrate and Phosphorus levels in surface water per TERUTI grid square	Rates of Nitrate and Phosporus by land-use (Turpin et al. 1997; Dorioz 2013)
Forests recreation	Inverse of minimum travel time from each grid square to forest areas	Shortest path routing using Dijkstra algorithm with French road network as graph (National Geographic Information)

Table 9: Rates of ecosystem services or disservices: water pollution no_ℓ, pho_ℓ and carbon sink intensity $co2_\ell$ for each land-use type l.

Rates	**Unit** /ha/year	**Pastures**	**Forests**	**Urban**	**Annual Crops**	**Perennial Crops**
Carbon sink $co2_\ell$	tCO2eq	0.37	5.06	0	-0.06	-0.06
Nitrate no_ℓ	kg	8.21	2	13.11	28	28
Phosphorus pho_ℓ	kg	0.6	0.12	1.425	1.6	0.12

Table 10: Aggregated acreage dynamics in km^2 of land uses $\sum_q h_l(t,q)$ over the New Aquitaine for each land-use class l and associated variation $\Delta(\%)$ from 2003 to 2053 for the three scenarios SQS: status quo scenario, CEAS: climate-economic adaptation scenario, BCS: biodiversity conservation scenario

SQS: Status-quo scenario

Year t	Perennial crops	Annual crops	Pastures	Forests	Urban areas
2003	2968	20984	25184	31320	4502
2013	2941	21088	24268	31643	5018
2023	2560	21127	23462	32621	5187
2033	2303	21076	22685	33495	5398
2043	2123	20949	21994	34289	5602
2053	1991	20776	21388	35013	5790
$\Delta(\%)$	-32	-1	-15	11	28

CEAS: Climate-economic adaptation scenario

	Perennial crops	Annual crops	Pastures	Forests	Urban areas
2003	2968	20984	25184	31320	4502
2013	3324	22901	22355	31207	5170
2023	3063	25049	19800	31793	5253
2033	3481	25589	17841	32410	5637
2043	3521	27931	14690	32845	5970
2053	5130	26413	13331	32953	7131
$\Delta(\%)$	72	25	-47	5	58

BCS: Biodiversity conservation scenario

	Perennial crops	Annual crops	Pastures	Forests	Urban areas
2003	2968	20984	25184	31320	4502
2013	3290	21802	24068	30846	4951
2023	2959	20965	26038	30485	4510
2033	3150	20552	26667	30174	4414
2043	3117	22855	24580	30014	4392
2053	4209	22236	23940	29417	5155
$\Delta(\%)$	41	5	-4	-6	14

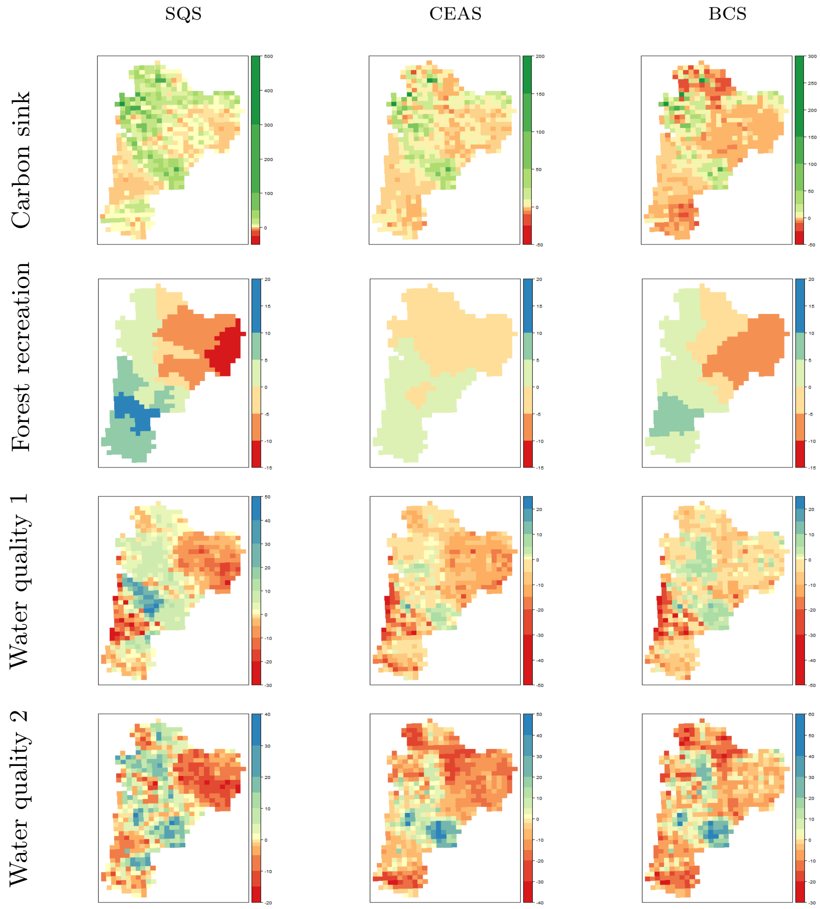


Fig. 8: Spatial distribution of ESs variation (2003-2053): Carbon sink (%), forest recreational service (%) and water quality (%).

Fig. 9: Effect of scenario SQS on bird index for 4 different habitat speciality. Each partially-linear curve represents a bird species.

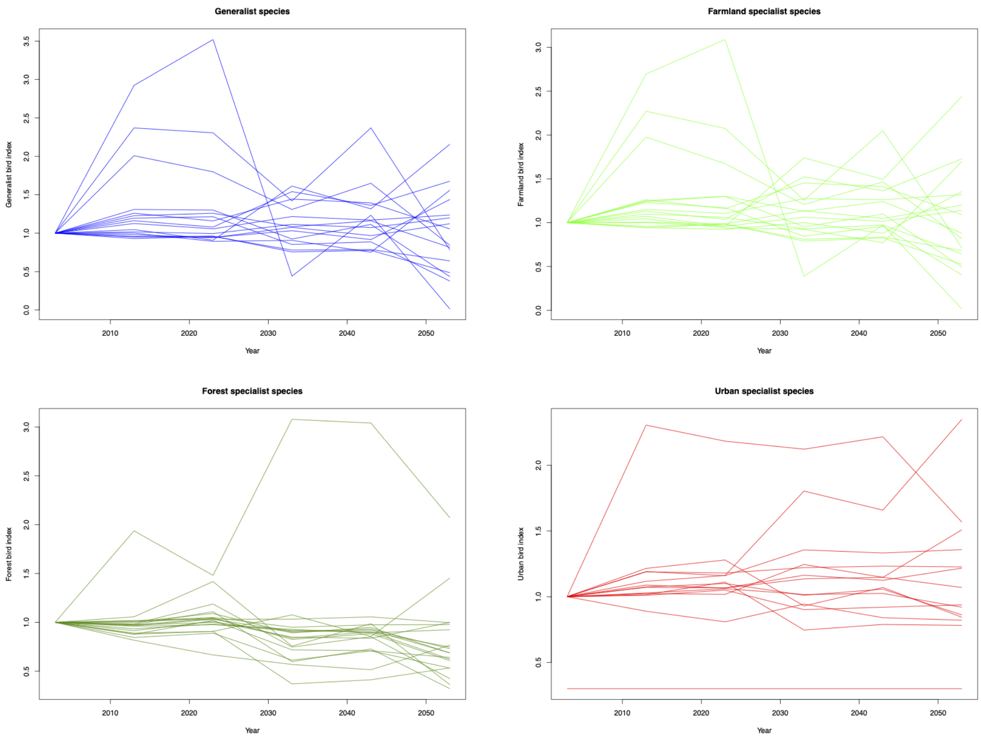


Fig. 10: Effect of scenario CEAS on bird index for 4 different habitat speciality.Each partially-linear curve represents a bird species.

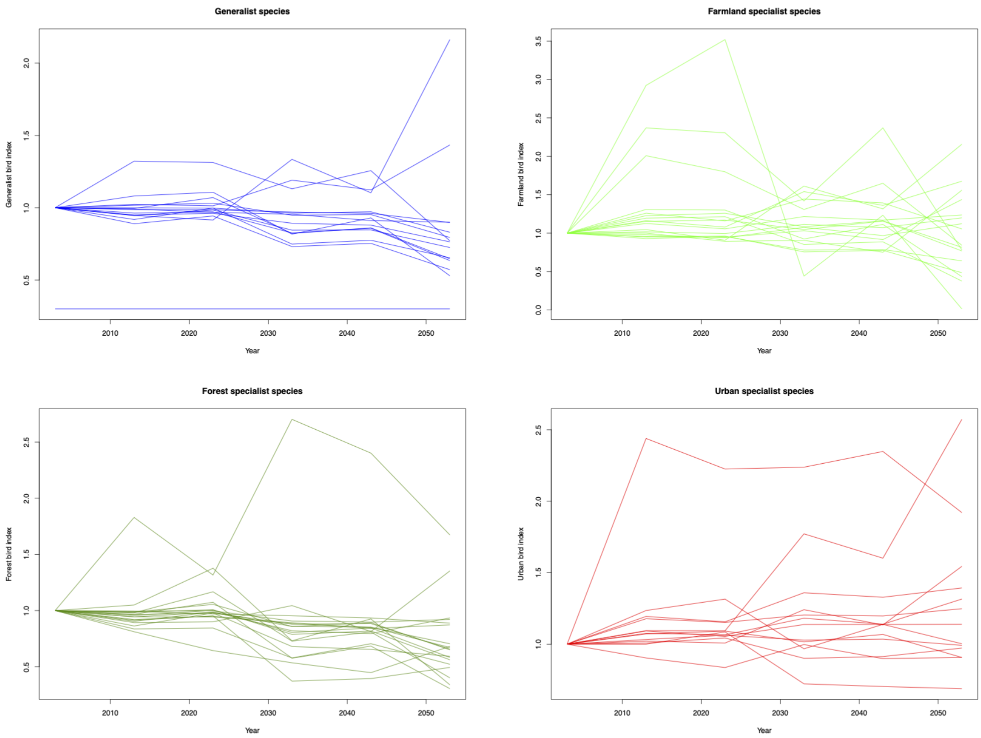


Fig. 11: Effect of scenario BCS on bird index for 4 different habitat speciality. Each partially-linear curve represents a bird species.