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Balance between climate change mitigation benefits and land use impacts of bioenergy: conservation implications for European birds

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Abstract

Both climate change and habitat modification exert serious pressure on biodiversity. Although climate change mitigation has been identified as an important strategy for biodiversity conservation, bioenergy remains a controversial mitigation action due to its potential negative ecological and socio-economic impacts which arise through habitat modification by land use change. While the debate continues, the separate or simultaneous impacts of both climate change and bioenergy on biodiversity have not yet been compared. We assess projected range shifts of 156 European bird species by 2050 under two alternative climate change trajectories: a baseline scenario, where the global mean temperature increases by 4 °C by the end of the century, and a 2 degrees scenario, where global concerted effort limits the temperature increase to below 2 °C. For the latter scenario, we also quantify the pressure exerted by increased cultivation of energy biomass as modelled by IMAGE2.4, an integrated land use model. The global bioenergy use in this scenario is in the lower end of the range of previously estimated sustainable potential. Under the assumptions of these scenarios, we find that the magnitude of range shifts due to climate change is far greater than the impact of land conversion to woody bioenergy plantations within the European Union, and that mitigation of climate change reduces the exposure experienced by species. However, we identified potential for local conservation conflict between priority areas for conservation and bioenergy production. These conflicts must be addressed by strict bioenergy sustainability criteria that acknowledge biodiversity conservation needs beyond existing protected areas and apply also to biomass imported from outside the European Union.

Keywords: biodiversity, climate change adaptation, climate change mitigation, complementarity, renewable energy, spatial conservation prioritization

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Introduction

Climate change: pressure on biodiversity and adaptation needs

Changes in the climate system affect ecosystems and communities across the globe, including those in the European Union (Bellard *et al*., 2012). Predicted future changes are expected to increase the extinction risk of species markedly (Thuiller *et al*., 2005; Fischlin *et al*., 2007; Gregory *et al*., 2009). Birds are facing climate pressure as well: despite their relatively good dispersal abilities, bird communities have been estimated to lag behind their respective climatic envelopes (Devictor *et al*., 2012). The majority of European bird species are expected to face losses of suitable range (Barbet-Massin *et al*., 2012).

While designation of protected areas under the European Union Birds Directive (European Parliament, 2010) has delivered demonstrated benefits for birds (Donald *et al*., 2007), 72% of the species of key conservation interest were assigned an unfavourable conservation status in the last EU-wide assessment (BirdLife International, 2004). Climate change is thus adding to a pre-existing conservation challenge for European birds.

Climate change adaptation is often associated with an increased need for land available for conservation action

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(Hannah *et al*., 2007). According to recent reviews, the most frequently suggested measures to adapt conservation to climate change include expanding the existing protected area networks with larger, more numerous and better connected protected areas (Heller & Zavaleta, 2009; Mawdsley *et al*., 2009). Indeed, protected areas have been demonstrated to play a role in facilitating recent species' range expansions (Beale *et al*., 2013). In addition, adaptive management, restoration and habitat creation as well as soft management of the matrix around protected areas have been suggested. Tools to effectively address both biodiversity and climate aspects in spatial planning exist but are not systematically used (Wilson & Piper, 2008).

The EU has taken on the ambitious target of halting the loss of biodiversity by 2020 and has established a strategy for reaching that target (European Commission, 2011). The main conservation policy tools in the EU are the Birds and Habitat Directives (European Council, 1992; European Parliament, 2010) through which the Natura 2000 network has been established. Natura 2000 areas are not strictly protected from human activity but rather allow 'sustainable management'. The actions that can be taken in a Natura 2000 area depend on the designation criteria. Climate change impacts require complementation of the Natura 2000 network, as areas are projected to become unsuitable for species that currently occupy them (Araújo *et al*., 2011; Maiorano *et al*., 2011).

In addition to establishment of protected areas, the biodiversity value of the matrix surrounding the protected areas should be retained as much as possible (Noss, 2001; Hannah *et al*., 2002). It is, therefore, essential that biodiversity considerations are also addressed in both energy policy and spatial planning. Developments in agricultural policy play a particularly important role, as 41% of the Special Protected Areas designated under the Birds Directive, and 38% of all Natura 2000 areas, are within agroecosystems (Condé *et al*., 2010), requiring careful planning to maintain their biodiversity values.

Bioenergy: potential for climate mitigation and land use conflict

The international community has agreed to limit climate change to below 2 °C above pre-industrial times under the United Nations Framework Convention on Climate Change (UNFCCC, 2010). Early and effective mitigation would also significantly reduce expected biodiversity loss due to climate change (Warren *et al*., 2013). However, current commitments to reduce greenhouse emissions are not sufficient to reach this target (UNEP, 2012) and enhanced mitigation action is required. Renewable energy, including bioenergy, is expected to play an important role in climate change mitigation (IPCC, 2011).

Biomass cultivation is a form of land use that competes with other uses such as food production (Dornburg *et al*., 2012). By replacing habitats and displacing other land uses, biomass production has consequences for habitat quality and availability for biodiversity. The impact on biodiversity depends on the type of bioenergy and the type of land use that is replaced. For instance, agricultural crops such as potato, rapeseed oil and maize have more negative impacts than wood-based ligno-cellulosic bioenergy crops, such as willow or poplar cultivated in a short rotation coppice (Paterson, 2009). Nevertheless, large-scale expansion of woody bioenergy plantations would have a negative impact on 28% of European species, while it would benefit only 10% of the species (Louette *et al*., 2010). Out of 36 ecological groups of birds defined in the Netherlands (Sierdsema, 1995 as cited by Londo *et al*., 2005), representatives of nine can be found in short rotation coppice (Londo *et al*., 2005). The majority of ecological groups cannot find suitable habitat in short rotation coppice plantations. Yet several studies have found that woody biomass, such as willow or poplar cultivated in a short rotation coppice, is more benign towards biodiversity than arable bioenergy crops (Paterson, 2009; Rowe *et al*., 2009; Fletcher *et al*., 2011).

An important question is whether adaptation strategies in conservation conflict with mitigation action through competition for space. To date, loss, degradation and fragmentation of natural habitats have been the most important drivers of the current biodiversity crisis (Sala *et al*., 2000; Millennium Ecosystem Assessment, 2005). Current extinction rates of species have been estimated to be several hundreds of times higher than the background rates (Dirzo & Raven, 2003). Various indicators show an alarming decline in biological diversity (Butchart *et al*., 2010), including in Europe (Gregory *et al*., 2004, 2009). Production of bioenergy is expected to add to this pressure.

Climate change and habitat conversion: quantifying the pressures

As the bioenergy debate continues to be heated, the scale of the impacts is often overlooked: do the impacts of mitigation actions outweigh the benefits of reduced climate change, or vice versa? We address this question with respect to bioenergy, separating expected impacts of climate change from mitigation-driven land use change on species. Although several studies have quantified the impacts of either climate change (Lawler *et al*., 2009; Thuiller *et al*., 2011; Barbet-Massin *et al*., 2012) or bioenergy (Eggers *et al*., 2009; Hellmann & Verburg,

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2010; Louette *et al*., 2010) on species distributions, the impacts of the two factors together have not been analysed to date (but see Alkemade *et al*., 2009).

Here, we examine the relative impacts of climate change and bioenergy in two alternative future scenarios. We project bird distributions under two regional climate change scenarios, and quantify the additional pressures created by bioenergy supply within the European Union. We ask how much pressure is exerted on European bird species of conservation interest directly by climate change and indirectly by bioenergy feedstock cultivation by 2050. In addition to evaluating the direct and indirect effects, we explore the potential spatial conflicts between bioenergy feedstock production sites and priority areas for expanding the existing Natura 2000 network, accounting for climate change impacts on species distributions. The outcome of our analysis provides guidance for policy planning to avoid trading off these two major goals against the other.

Materials and methods

Scenarios of climate and land use change

We examined the impacts on European birds up to the year 2050 under two scenarios. In one scenario, global emissions are reduced sufficiently to limit the global mean temperature rise by 2100 to below 2 °C (with medium probability). In the other scenario, global mean temperature is on a trajectory to increase by 4 degrees by the end of the century due to lack of mitigation effort.

To model the development of land use under different policy scenarios, we used previously published scenario outputs from the integrated assessment modelling framework IMAGE 2.4 (MNP, 2006) that simultaneously accounts for changes in emissions and land use. Land use in the 2 degrees scenario was based on the '450 ppm *Core*' scenario, developed for the OECD Environmental Outlook (OECD, 2012), while the baseline scenario of the OECD study was used for land use in the 4 degrees scenario. This baseline represents a scenario without new climate policies and without major changes in preferences or behaviour. The 450 ppm *Core* scenario was better suited for our analysis than those of the IPCC Special report on emission scenarios (SRES; IPCC, 2000), given that the 450 ppm *Core* scenario considers strong concerted global effort to mitigate climate change (van Vuuren *et al*., 2011). Global scenarios balance the overall supply and demand of biomass for both food and energy, which is their strength compared to regionally developed scenarios of agricultural land use. Although the spatial resolution and allocation rules do not allow spatially detailed conclusions, they do provide estimates of the magnitude of impacts at a continental level (Meller *et al*., 2013).

For modelling responses of biodiversity, climatic circulation models are essential, because they reflect variation and extremes. However, data from process-based climatic circulation models for the recent representative concentration pathways (RCP) or OECD scenarios are currently not available at a resolution suitable for our analysis. This is why we projected our bird distributions using climatic data from regional climate models based on the SRES scenarios. The SRES scenarios assume socio-economic development in the absence of climate policy and do not take into account strong concerted effort to mitigate climate change. Therefore, none of them reaches the 2 degrees target. However, the B1 SRES scenario reasonably represents a '2 degrees future' up to 2050 (only after 2050, climatic conditions start to diverge more strongly between the B1 and a 2 degrees trajectory). The A2 scenario is, in terms of predicted increase in radiative forcing, comparable to a scenario where the global average temperature increases by 4 degrees by the year 2100 compared to pre-industrial time (IPCC, 2007).

Bird data

We used distribution data across the Western Palearctic region for 156 bird species included in the EU Birds Directive Annex I (European Parliament, 2010). We chose this set of species as indicators of conservation value, as they have a legal conservation status within the European community. Presence–absence data for the species were obtained from the EBCC atlas of European breeding birds (Hagemeijer & Blair, 1997), which we further completed for Northern Africa and Eastern Europe by geo-referencing and digitizing breeding bird distribution maps from the handbooks of the birds of the Western Palearctic at a 0.5 degree resolution (BWPi, 2006; see Barbet-Massin *et al*., 2012 for details). Three species that occurred in less than 20 cells across the Western Palearctic region were excluded from the analysis to ensure enough information for building the distribution models.

To compare the impacts in different groups of species, we classified the species into seven habitat groups based on species-specific expert descriptions of breeding habitats in Hagemeijer & Blair (1997): generalists found in multiple habitat types; forest generalists; open habitat generalists; wetlands and aquatic habitats include species associated to such environments; old growth forest specialists; farmland specialists; and open natural habitat specialists (Table S1). As Hagemeijer and Blair did not consider short rotation coppice as a habitat type, we complemented the information with a long-list of breeding birds found in short rotation coppice fields (Londo *et al*., 2005). The impact of bioenergy on species was defined as negative, neutral or positive, depending on the habitat association of the species (see Table S1 for the classification).

Climate data for predicting future bird distributions

We selected five uncorrelated climatic variables to represent current climate from the Worldclim database (Hijmans *et al*., 2005): temperature seasonality (standard deviation × 100), maximum temperature of the warmest month, minimum temperature of the coldest month, precipitation of the wettest month and precipitation of the driest month.

We used a set of regional climate models (RCM) derived from the 4th assessment report of the IPCC under two climatic scenarios that correspond to the 2 degrees and 4 degrees scenarios: the B1 and A2 scenarios. Projections of monthly temperatures and precipitation for the years 2001–2050 were generated by the Rossby Center Regional Climate Model (RCA3; Samuelsson *et al.*, 2011), driven by the global ECHAM5 (Roeckner *et al.*, 2003) circulation model. Up to 2050, these climatic scenarios globally show only minor divergence: the difference between global mean temperatures is less than 0.5 degrees. The difference is projected to become more pronounced towards the end of the century. However, regional differences are more substantial already in the next few decades: for example, the regional circulation models project that the minimum temperature of the coldest month is already 4 °C higher in the A2 scenario than in B1, and precipitation of the driest month is 7% higher in B1 than in A2 by 2050.

We had to exclude Cyprus as well as the Canary islands from the analysis because they were located outside the extent of the RCMs.

Projections of future bird distributions

We obtained an ensemble of predicted species distributions for each of the 156 species. The ensemble included projections based on several modelling techniques: Generalized Additive Models (GAM), Boosting Regression Trees (BRT), Classification Tree Analysis (CTA), Multiple Adaptive Regression Splines (MARS) and Random Forest (RF), all implemented in the BIOMOD package in R (Thuiller *et al.*, 2009). Models were calibrated for the baseline period using a random sample of 65% of the initial data and evaluated against the remaining 35% of the data. We calibrated the models over the whole Western Palearctic at a resolution of 0.5° and projected the future distributions over Europe at a resolution of 10′.

The model predictions were transformed into binary presences and absences with a threshold that maximizes the True Skill Statistic (TSS). The TSS score was used to evaluate model performance. This analysis was repeated five times, thus providing a fivefold internal cross-validation of the models. The ensemble was then summarized into a consensus. The ensemble approach has recently been suggested in the literature, because the choice of modelling technique is an important source of variability in predicted species distributions (Buisson *et al.*, 2010) and consensus methods have been shown to perform better than single models for predicting the current ranges of species (Marmion *et al.*, 2009). To obtain the consensus projections, we used a technique called *committee averaging*, where the predicted probability of occurrence is calculated as the average across the binary projections of single models (Thuiller *et al.*, 2009).

Predicted future bioenergy area

We used two previously published global scenarios of global land use driven by demand for food, energy and other resources, as well as policies to mitigate climate change (OECD, 2012). The land use change scenarios until 2050 were obtained with the integrated modelling framework IMAGE2.4 (MNP, 2006). Land use patterns reflecting global effort to meet the 2 degrees target were contrasted with a baseline scenario (corresponding to an increase in the global mean temperature by 4 degrees by 2100). The land use projections of the scenarios were available on a grid of 0.5° resolution.

In IMAGE2.4, land use for bioenergy under these two scenarios is allocated by ranking grid cells according to their suitability. This is a function of potential crop yields, distance to rivers, distance to roads, and distance to current agricultural land. The total amount of potentially available bioenergy is determined on the basis of calculations of the IMAGE crop model. The potential bioenergy supply is restricted by several criteria. Most importantly, bioenergy is only allowed on abandoned agricultural land and on part of the natural grasslands. Bioenergy is not allowed on water scarce areas or severely degraded areas. The costs of primary bioenergy crops (woody, maize and sugar cane) are described using a Cobb-Douglas production function using labour costs, land rent costs and capital costs as input. The costs of land are based on average regional income levels per km^2. These production functions have been calibrated with empirical data (Hoogwijk, 2004). Next, the biomass model describes the conversion of the available biomass into two generic secondary fuel types: solid and liquid fuels. The solid fuels are used in industry and power generation, and the liquid fuels are used in other sectors, in particular transport. Maps describing the distribution of different land cover types are produced as an outcome of the allocation (Figure S1).

In the 2 degrees scenario, bioenergy in the EU consisted of woody bioenergy (about 38% of total bioenergy production by 2050) and residues (about 62% of total bioenergy production by 2050). Cultivation of other bioenergy crops was found not to be cost-effective in the EU when the supply restrictions mentioned above were accounted for.

In the 2 degrees scenario, by 2050, bioenergy accounted for 25% of the primary energy production in the EU and replaced energy from fossil sources especially in heat and power generation. The land area required for bioenergy crops was 1 38 000 km^2 (compared to 2.2 million km^2 agricultural land area by 2050 and only 5000 km^2 of land area for bioenergy crops in the baseline). The total forest area in the EU is 5% smaller in the 2 degrees scenario than in the 4 degrees scenario (Figure S2). As we analyse the land use pattern within the EU, we do not consider the impacts of the imported biomass, which accounted for 40% of the total bioenergy demand. In the 2 degrees scenario, primary energy obtained from biomass was 160 EJ yr^{-1} in 2050. Estimates of the sustainable global bioenergy potential in different studies range between 130 and 500 EJ yr^{-1}, after accounting for food, water and biodiversity conservation needs (Beringer *et al.*, 2011; Dornburg *et al.*, 2012). Biomass use for energy in the OECD scenario thus lies in the lower end of the estimated potential range.

Expected range size changes due to climate change and bioenergy

The expected change in range size for each species was calculated as the relative difference between the total area of cells where the species was predicted to be present under current climate conditions and the area of cells where the species was predicted to be present under future climate conditions. This was calculated separately for the two regional climate change scenarios. To make interpretation of the results more straightforward, the predicted probabilities of occurrence were transformed into binary presences and absences: if the committee average was more than 0.5, meaning that more than half of the models predict a given species to be present in a cell, it was considered present. We accounted for the latitudinal variation in grid cell sizes by weighting each predicted occurrence by the size of the corresponding grid cell.

The regional climate model projections allowed us to quantify the change in climatically suitable range size. For the 2 degrees scenario, we also quantified the additional change in suitable range size due to overlap of projected future range and bioenergy sites. These additional changes can be positive for certain species and negative for others, depending on habitat preferences of the species.

Priority areas for conservation

We used the spatial conservation prioritization software Zonation (Moilanen *et al.*, 2009, 2012) to identify conservation priorities to complement the existing Natura 2000 network with four different criteria: (i) current suitability, (ii) future suitability, (iii) areas that retain climatic suitability for species that are predicted to experience a loss in range size, (iv) areas that are predicted to become climatically suitable for species in the future and thereby potentially allow range expansions. We performed this analysis for only the 2 degrees scenario, where bioenergy plays a role in terms of land use, and where spatial conflicts could thus be anticipated.

To distinguish between sites with low and high suitability for each species in the current and future scenarios, we used continuous probabilities of occurrence obtained by first transforming the predictions from each modelling technique to presences and absences with the threshold that maximizes the true skill statistic, and then calculating the mean over those predictions. To identify priority areas for retention and expansion, we used binary data describing whether a cell is predicted to be either a retention or expansion cell (value 1) or not (value 0).

Zonation identifies networks of areas that represent as much of the biodiversity features as possible while minimizing costs or required area. In such a conservation prioritization analysis, planning units (here, 10′ cells) are removed from the landscape so that the marginal loss of biodiversity value at each removal is minimized. We used the core area Zonation (CAZ) algorithm to determine the biodiversity value in each cell. The algorithm defines the biodiversity value as the maximum value across species in that cell and can be expressed as $\delta_i = \max(q_{ij}w_j/c_i), j$

where δ_i is the marginal biodiversity value loss that occurs with removal of cell i, q_{ij} is the proportion of the remaining distribution of species j in cell i, w_j is the species-specific weight for species j, and c_i is the cost of cell i. We did not use species-specific weighting or cost data, so these values were equal for all species and cells. We forced the existing Natura 2000 areas to be assigned the highest priority, considering a grid cell as included in the network if 50% or more of its area was covered by Natura 2000. This allowed us to acknowledge that a part of the landscape, and species distributions, were already under protection, and seek areas that would most effectively complement the existing protection.

Effectively, the core area Zonation algorithm assigns highest value to cells with high suitability for rare species. We used the best 10% of cells of the Zonation ranking as the set of priority areas for which we identified overlap between different scenarios and potential conflicts with bioenergy feedstock cultivation. We calculated the proportion of the priority areas that overlap with bioenergy cells. To assess whether bioenergy cells have more or less overlap with conservation priorities than the same area of randomly selected sites, we made 100 random selections and calculated the overlap between conservation priority areas and the randomly selected cells.

Results

Climate change drives larger changes in range size than bioenergy

Overall, we found that climate change alone in the 4 degrees climate trajectory was expected to contract the range of three more species than in the 2 degrees scenario. The magnitude of range contractions was higher in the 4 degrees scenario. In the 4 degrees scenario, the median contraction in climatically suitable range was 40%, whereas the median contraction in the 2 degrees scenario was 28%, both when considering only climate and the joint impacts of climate and bioenergy (Table 1). Gains and losses in range size were predicted to occur across all habitat groups (Fig. 1). For seven species, the negative impact of bioenergy outweighed the positive impact of reduced climate change in the 2 degrees scenario.

Overall, the effect of climate change on species range was projected to be much larger than the effect of bioenergy in the particular mitigation scenarios we used in our analyses. For individual species, the change in range varied between species losing suitable range almost completely (*Acrocephalus paludicola* lost 98–100% of its range) to one species, *Emberiza cinerea,* gaining more than 20 times of its current range in the 4 degrees scenario and 10 times in the 2 degrees scenario. This compares to changes in range due to bioenergy in the 2 degrees scenario of between −38% and 4%, with a median change of −2.6%. Additional impacts from climate change in the 4 degrees scenario were larger than land use impacts from bioenergy in the 2 degrees scenario, when compared to the impacts of 2 degrees of climate change only (Fig. 2).

In all habitat groups, some species were expected to be impacted by climate positively and some negatively. However, positive impacts of bioenergy were confined

Table 1 Proportional changes in species range sizes under the different scenarios. Median and mean proportional decrease are given across species for which range size is decreasing, while median and mean proportional increase are reported across species for which range size is increasing. The number of species losing different proportions of their range as well as the number of species with expected increases in range size is reported for all scenarios

	Median (mean) decrease%	Median (mean) increase%	Number of species losing range						Number of species gaining range
			0–10%	10–25%	25–50%	50–75%	75–90%	90–100%	
2 degrees scenario (Climate only)	28 (32)	26 (38)	11	7	29	5	3	1	100
2 degrees scenario (Climate and bioenergy)	28 (30)	25 (38)	16	7	31	5	3	1	93
4 degrees scenario (Climate only)	40 (39)	29 (54)	12	4	30	5	5	3	97

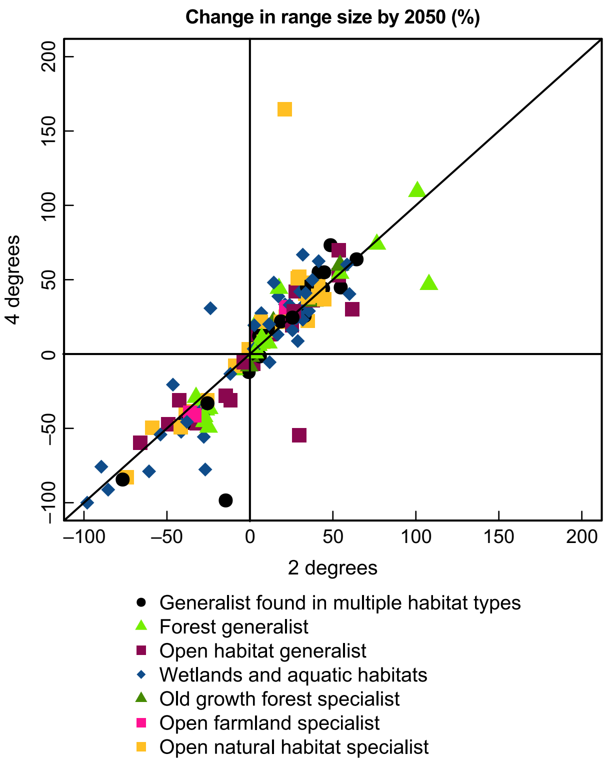

Fig. 1 The proportional change in range size of bird species between present time and the year 2050 in the 2 degrees scenario (*x* axis) or 4 degrees scenario (*y* axis) due to climate change only. One species with an exceptionally large proportional increase in range size (*Emberiza cinerea* with 1150% increase in 2 degrees scenario and 2125% increase in 4 degrees scenario) has been removed from the figure.

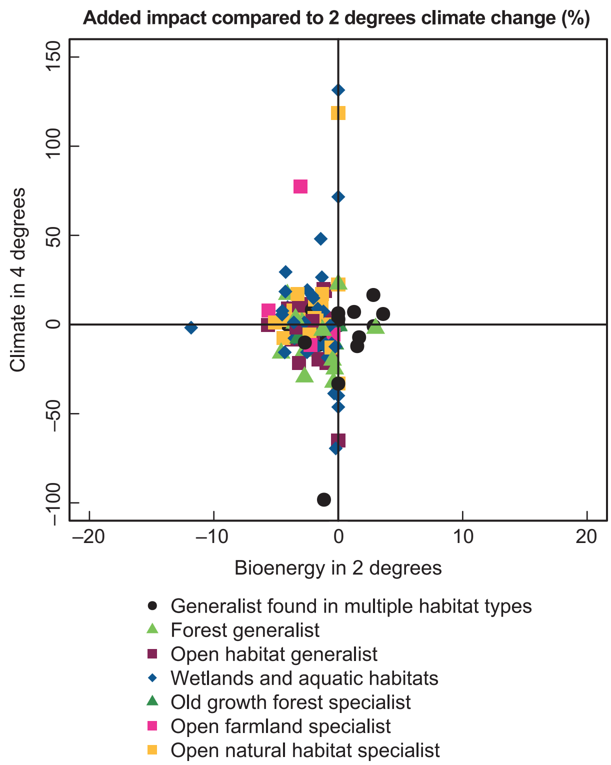

Fig. 2 The additional proportional change in suitable range sizes of bird species due to bioenergy in a 2 degrees scenario (*x* axis) and climate in a 4 degrees scenario (*y* axis) between present time and the year 2050 compared to impacts from climate only in a 2 degrees scenario. One species with an exceptionally large overlap between bioenergy and climate change impact (*Acrocephalus paludicola* with overlap of 33.3% and a negative impact from bioenergy, and -100% added range size change from 4 degrees climate change) has been omitted from the figure.

to six generalist species found in several habitat types and one forest generalist species (Fig. 2). While the magnitude of climate change impacts was stronger than the impact of bioenergy, bioenergy was predicted to have a negative impact on a larger proportion of the species (96%) than climate (36% of species in the 2 degrees scenario and 38% of species in the 4 degrees scenario).

Potential conflict between bioenergy and biodiversity conservation

Overlap with bioenergy ranged from 1.9 to 4.2% of the conservation priorities, depending on the prioritization criteria, while the median overlap with random sites was from 2.6 to 2.8%. Overlap of bioenergy with conservation priorities was significantly higher than with random areas for three of the prioritizations: current suitability, future suitability and species retention (see Figs 3a–c and 4). In contrast, overlap between conservation priority areas based on species range expansion and bioenergy was lower than with random cells (Figs 3d and 4).

Discussion

Climate change mitigation is an important conservation strategy

The scale of range loss for European Birds Directive species depends on the magnitude of climate change. Qualitatively, impacts were similar in the two climate scenarios for most species, but the magnitude of change

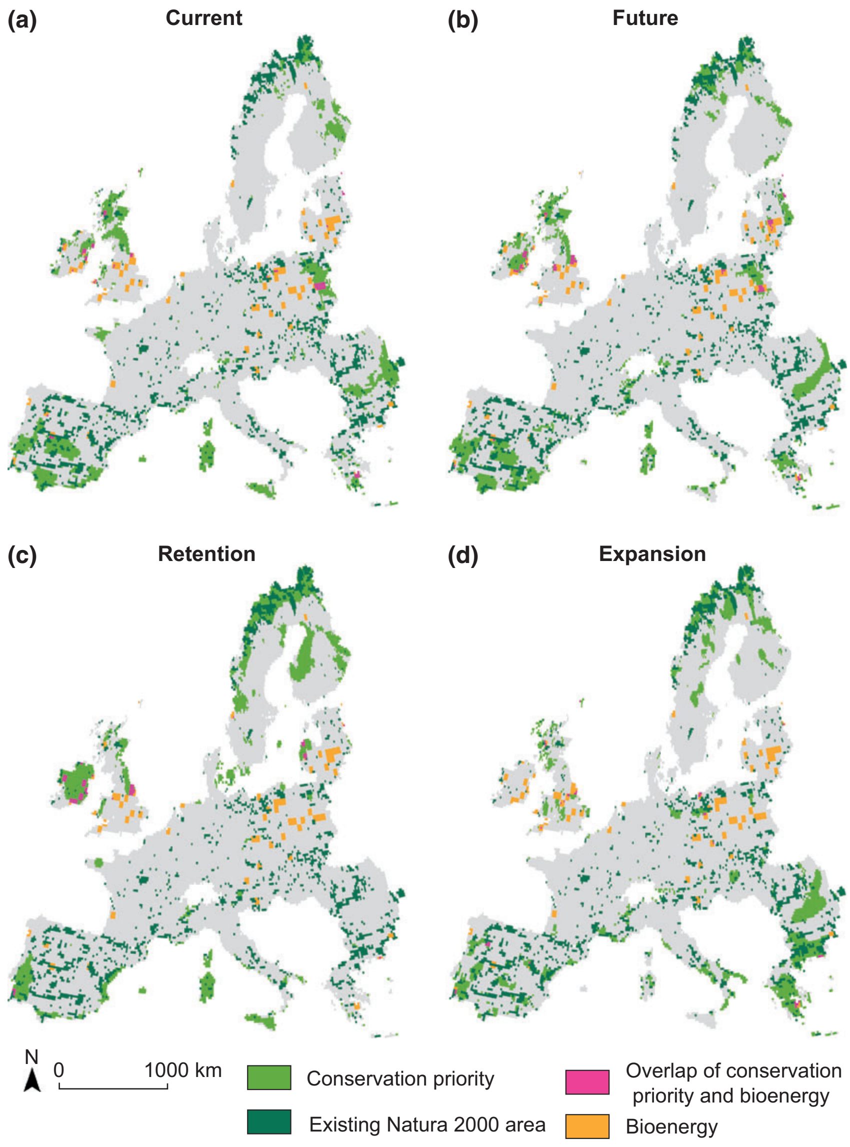

Fig. 3 Priority areas to complement the existing Natura 2000 network based on four criteria: (a) current climatic suitability, (b) predicted future climatic suitability, (c) retention areas for species predicted to lose range and (d) expansion areas of climatic suitability in the year 2050 in a 2 degrees climate scenario.

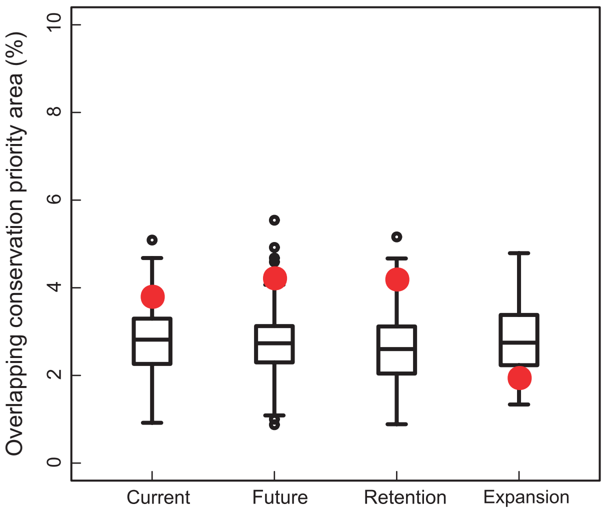

Fig. 4 Proportion of conservation priority areas overlapping with bioenergy sites (red dots) and a corresponding area of randomly selected sites (boxes). Conservation priorities based on four criteria are presented from left to right: current climatic suitability, predicted future climatic suitability, areas of retention and expansion of climatic suitability in 2050 in a 2 degrees scenario. The boxplots display the median as well as the 50% (box) and 95% (whiskers) confidence intervals.

was higher in the 4 degrees scenario. The difference in impacts is striking, considering that the difference in global mean temperature between the two scenarios is less than 0.5 degrees in 2050. The climate change scenarios are expected to diverge more towards the end of the century, when the benefits of mitigation would become even more apparent than they are within the next 40 years (Warren *et al.*, 2013). However, our results also show that many European birds of conservation concern face negative impacts of climate change even in the 2 degrees scenario. Conservation policy and action will be needed to facilitate successful adaptation of these species. The average impact of bioenergy on range loss was small.

Loss and gain of suitable climatic space was evenly distributed across all habitat groups. Contrastingly, all species considered to benefit from bioenergy expansion were generalists (Fig. 2) – species likely to find suitable habitat under any scenario. This finding supports previous research suggesting that increased bioenergy production is unlikely to benefit threatened species (Fletcher *et al.*, 2011; Langeveld *et al.*, 2012).

On average, the overlap between conservation priorities and bioenergy was higher than expected by chance for three out of four prioritization criteria. While the overall overlap was small due to the limited extent of bioenergy feedstock cultivation, we identified the potential for local conflict between bioenergy production and biodiversity conservation.

Spatial resolution and uncertainty: scope for further research

The limited level of detail in the spatial allocation rules of the IMAGE land use module limit the conclusions to be drawn based on our results. For example, the land use projections available for 2050 do not account for regional policy or for logistics in the production chain, which limits their level of spatial detail (Meller *et al.*, 2013). However, feedstock choice and geographical location have an effect on the environmental consequences (Davis *et al.*, 2011; Immerzeel *et al.*, 2013), and management is important for biodiversity outcome in short rotation coppice (Londo *et al.*, 2005; Fletcher *et al.*, 2011). At the 0.5 degrees resolution, bioenergy production seems unrealistically aggregated, although production chain logistics also favour aggregation in reality (Hellmann & Verburg, 2011). Smaller scale production would increase heterogeneity in the European agricultural landscape, and therefore add biodiversity value (Londo *et al.*, 2005; Rowe *et al.*, 2011; Northrup *et al.*, 2012) to the landscape as a whole. Regional land use dynamics and sustainable bioenergy harvesting levels have been modelled at a high spatial resolution with methodologies including Multi-Criteria Evaluation (Hellmann & Verburg, 2011), Compromise Programming (Sacchelli *et al.*, 2013) and Agent-Based Modelling (Murray-Rust *et al.*, 2013). The CLIMSAVE Integrated Assessment Platform provides a user interface for studying climate change impacts, adaptation and vulnerability in different policy sectors in alternative future scenarios at a regional level (Harrison *et al.* 2013; http://climate-adapt.eea.europa.eu/climsave-tool). Such methods could be used to project the consequences of specific EU bioenergy policies, thereby enabling to further understand the impacts of alternative policy options on land use dynamics and habitat structures.

As the land-use projections do not specify where logging residues are collected (van Vuuren *et al.*, 2010), it is not possible to assess what the biodiversity impacts of forest biomass extraction are in these scenarios. Our results are, therefore, likely to underestimate the negative impacts of bioenergy, especially with regard to species in old growth forests.

We focused on land use impacts of bioenergy within Europe and did not consider the land use impacts of European bioenergy demand overseas. In the 2 degrees scenario, 40% of all primary bioenergy demand is met with imported biomass. Impacts of land use change and fragmentation are likely to be more dramatic in locations where human fingerprint on the landscape is not yet as prominent as it is in Europe. Previous studies have demonstrated detrimental impacts on biodiversity especially in the tropics, where biologically diverse and

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unique habitats have been converted to bioenergy plantations (Koh, 2007; Koh & Wilcove, 2008).

Our results reflect the impacts of climate and bioenergy land use on the amount of available habitat among birds of European conservation concern, and the risks of conflict between different land use interests. However, the resolution of our spatial projections, and the uncertainty associated with the predictions, does not allow accounting for the effects of landscape structure through population dynamics. We quantify 'impact' as a reduction in climatically suitable area or area converted to unsuitable habitat. Area and extent of occurrence are widely used predictors of extinction risk (Brooks *et al.*, 1997; Lee & Jetz, 2011). However, the impacts of climate change differ to some extent from those of land use change. Climate change, for an organism, is a gradual change in the quality of environment. Responses to climatic changes include changes in physiology or behaviour, shifts in space or time and extinction (Bellard *et al.*, 2012). Land use change is more akin to a step change: one habitat type changes into another. If the new habitat is unsuitable, the populations can only respond by shifting in space or going extinct. Sensitivity of species to both changes varies depending on their adaptive capacity, determined by population dynamics and life history traits (Dawson *et al.*, 2011; Foden *et al.*, 2013).

We calibrated our distribution models using data that extend to Northern Africa (Barbet-Massin *et al.*, 2010) and predicted the future climatic suitability by ensemble forecasting to reduce uncertainty in the predictions (Araújo *et al.*, 2005). Nevertheless, such predictions are always subject to uncertainty (Buisson *et al.*, 2010; Garcia *et al.*, 2011) and conservation priority areas based on them can only be regarded as a 'rough guide' (Williams *et al.*, 2013). However, our results showed clear general trends in regard to the magnitude of change.

Sustainable bioenergy policy needs more clarity

While our results cannot be interpreted as the specific locations where land use impacts and conservation conflicts are projected to take place, given the uncertainty in future scenarios and the coarse resolution of the land use projections, they improve the current understanding about synergies and trade-offs between climate change mitigation and biodiversity conservation at the European scale. Our results are in line with previous work suggesting that climate change mitigation is an important conservation strategy (Rogers & McCarty, 2000; Hannah *et al.*, 2007; Foden *et al.*, 2013; Warren *et al.*, 2013). The impacts of increased bioenergy are less extensive than the impacts of climate change in the 2 degrees trajectory. However, cultivation of bioenergy is expected to turn the net change in range size from positive to negative for seven species. Where and how bioenergy is produced thus becomes an important question.

We studied climate change impacts from the perspective of European birds. We do not address the impacts of our scenarios on food security or international conservation. Our results are not meant to provide information about the sustainability of currently available biofuels. Rather, we address the role of bioenergy in climate mitigation strategies on a longer term and from the perspective of the whole energy system. In the OECD Environment Outlook scenarios, biomass is primarily used in heat and power generation.

Our land use scenario predicts a limited extent of bioenergy feedstock cultivation in Europe. However, we identified potential for local conflict between bioenergy sites and priority areas for conservation. This potential highlights the need to clarify the sustainability criteria for bioenergy and explicitly define what are 'areas with high biodiversity value' (Eickhout *et al.*, 2008). Similarly clarified criteria must apply to imported biomass as well.

It should be noted that in the mitigation scenarios we used, bioenergy is only one element of a wide mitigation portfolio. In this sense, we have compared the positive effects of all mitigation efforts with the negative effects of only bioenergy. A comparison between a 4 degree scenario with a scenario with bioenergy as the only mitigation measure would very likely result in the negative effects of bioenergy outweighing the positive effects. Scenarios which consider the effectiveness of policy mixes in more detail can provide additional information about the mitigation potential of bioenergy.

The role of bioenergy may be smaller if policies limit carbon capture and sequestration from bioenergy (BECCS) or decrease the demand of biofuels by subsidizing electric cars (Deetman *et al.*, 2013) that would also reduce its environmental impact. In the OECD 450 ppm *Core* scenario, the total primary energy from biomass amounts to 160 EJ yr^{-1} in 2050. This is in the lower range of estimates of sustainable global bioenergy potentials (130–500 EJ in different assessments; Beringer *et al.*, 2011; Dornburg *et al.*, 2012). If biomass were to play a larger role in the global energy mix, its environmental impacts and associated land use conflicts would undoubtedly become more prominent than is currently indicated by our results. Another recent assessment finds that limiting climate change, reducing biodiversity loss and stimulating sustainable development to eradicate poverty are broadly compatible – but concludes that 'marginal improvements will not suffice; large, transformative changes are needed to realise sustainable development' (PBL, 2012).

Further assessments of the land use impacts of such scenarios can provide important insights for policy design. Scenarios of global boundary conditions can be brought to a more spatially explicit level through process-based modelling that accounts for regional policy and logistics (Meller *et al.*, 2013). Identifying pathways and policies to achieve low levels of greenhouse gas concentrations while keeping land use impacts to a minimum remains a challenge for society.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Breeding habitats and qualitative impact of bioenergy on bird species included in the analysis.
Figure S1. Projected land cover in the European Union.
Figure S2. Projected changes in the extent of different land cover types within the European Union.