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RESEARCH ARTICLE

Time to consider the timing of conservation measures: Designing cost-effective agri-environment schemes under climate change

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Abstract
Climate change is one of the largest threats for biodiversity as changing climatic conditions often make existing habitat sites less suitable. This poses new challenges for species conservation, in particular in agricultural landscapes, where climate change may also induce modifications in agricultural land use. To conserve species in agricultural landscapes, agri-environment schemes (AES) which compensate farmers for implementing conservation measures are commonly used. However, current research on the cost-effective design of AES largely ignores necessary adaptations of conservation measures given climate change. We develop a climate-ecological-economic (CEE) model to examine how the cost-effective design of AES has to be modified under climate change. We apply the model to the conservation of eight meadow bird species in Northern Germany and determine the cost-effective conservation measures under recent and future climatic conditions. We find that the timing of conservation measures in the AES needs to be changed in the RCP8.5 scenario given the species' phenological adaptations and the impact of extreme events (inundations) on costs. The novelty of the research lies in the development of a CEE model which considers both spatial and temporal changes in costs and benefits to develop recommendations for the cost-effective design of AES under climate change.

Keywords: climate-ecological-economic model; conservation measure; cost-effectiveness; desynchronization; ecological-economic model; farmland birds; grassland; payments for ecosystem services (PES)

JEL Classifications: Q15; Q18; Q54; Q57; Q58

Introduction
Global biodiversity is in decline, and intensive agricultural land use is one of the most important threats to species (Cole et al. 2021; Dasgupta 2021). One policy option to

conserve species in agricultural landscapes is the implementation of incentive-based instruments (Khanna et al. 2018) such as payments for ecosystem services (PES) or – as they are often referred to in an agricultural context – agri-environment schemes (AES) (Chakrabarti et al. 2019; Dakpo et al. 2021; Lichtenberg 2021; Duke et al. 2022). An AES typically contains various conservation measures defined by restrictions on land use and measure-specific payments (Mennig and Sauer 2020). The decision problem of the farmers is to select the land use that maximizes profits, which implies the decision of whether or not to participate in the AES and – if the AES offers the farmer the opportunity to select between different measures – which conservation measure to implement (Ohl et al. 2008).

For economists, a key criterion to assess the suitability of an AES is its cost-effectiveness (Messer 2006; Armsworth et al. 2012; Duke et al. 2013; Bartkowski et al. 2021). Previous research has examined the cost-effectiveness of conservation measures, taking into account that both the benefit and costs of a measure are spatially heterogeneous and differ between different conservation measures (Lewis et al. 2011; Duke et al. 2014; Wätzold et al. 2016). However, under climate change, initially cost-effective conservation measures may need to be adapted to remain cost-effective (Ando and Mallory 2012; Pecl et al. 2017; Reside et al. 2018). To develop recommendations for the necessary adaptations, the impact of climate change on both the species and on costs of conservation measures has to be considered (Gerling et al. 2022a).

Research so far has focused on impacts of climate change on the spatial dimension of conservation (Alagador et al. 2014, Alagador et al. 2016; Dasgupta 2021). Under changing climatic conditions, previously suitable habitat sites may no longer be so. However, other sites – typically sites further poleward or uphill – may become more suitable given these climatic changes (Oliver et al. 2016). Additionally, the opportunity costs of conservation may change in a spatially heterogeneous manner, as some sites become more suitable for agricultural production (resulting in increasing opportunity costs if agricultural production is restricted for conservation purposes), while others become less productive (Rashford et al. 2016; Ray et al. 2019; Lachaud et al. 2021). Previous research has hence focused on the cost-effective provision of habitat sites in this "new climate space" (Vos et al. 2008) and/or on providing migration pathways towards these areas (Alagador et al. 2014, Alagador et al. 2016; Gerling et al. 2022a, Gerling et al. 2022b).

However, in agricultural landscapes, the temporal dimension also plays an important role as the timing of agricultural land use relative to the timing of a species' critical life cycle stages has a strong impact on habitat suitability (Wätzold et al. 2016). Changing climatic conditions have complex impacts on the temporal dimension of conservation as they may impact a species inhabiting agricultural landscapes both directly (by altering the climatic conditions of the habitat and hence, the timing of life cycle stages) and indirectly (by inducing changes to the timing of agricultural land use which in turn influence the species). For example, Santangeli et al. (2018) examine the case of two ground-nesting farmland bird species which used to be well adapted to the timing of land use as they lay their eggs after the farmers have sown the fields. The nests are then not disturbed by any farming operations until the birds have left the nests. Under climate change, the species lay their eggs increasingly early and farmers have also advanced the timing of sowing. However, the adaptation of the birds is stronger than that of farmers, meaning that birds lay their eggs increasingly on unsown fields and nests are likely to be destroyed by the subsequent land use (Santangeli et al. 2018). When the species' and farmers' climate change adaptations are of a different magnitude, temporal desynchronizations thus pose an additional, indirect threat to species under climate change.

Temporal desynchronization processes may be relevant for the design of conservation measures as many measures in the context of AES focus on the timing and frequency of land use. A prominent example is biodiversity-enhancing mowing regimes which prohibit mowing during a certain time frame to protect species during their most susceptible life cycle stages (Johst et al. 2015). Such schemes exist all over the world including the USA (Perlut et al. 2011; Chakrabarti et al. 2019; Allen et al. 2021) and Europe (Kleijn et al. 2006; Wätzold et al. 2016; Cong et al. 2020). However, given the fixed timing of harvest restrictions in many AES in Europe (Wätzold et al. 2016) and the USA (e.g., the "haying and grazing practices" according to primary nesting periods of the US Conservation Reserve Program (USDA n.d., USDA 2020)) and possible phenological adaptations of the target species under climate change, the resulting desynchronization may make AES less cost-effective. Regarding cost-effectiveness analysis, one also has to consider that climate change typically leads to a temporal advancement of the profit-maximizing land use (Cui and Xie 2021), implying that the costs of a conservation measure with a fixed timing may change under climate change (Huber et al. 2017).

In this article, we develop a modelling approach which combines ecological-economic modelling (Polasky et al. 2011; Jiang and Swallow 2017, Drechsler et al. 2022) with a climate model to a climate-ecological-economic (CEE) model in order to design a cost-effective AES and determine its necessary adaptations under climate change. To the best of our knowledge, our approach is novel in two ways. It is the first to analyze how to design cost-effective AES under climate change, and it considers not only spatial but also temporal changes in conservation costs and impacts on species due to climate change. With our CEE model, we examine the cost-effective design of an AES consisting of different conservation measures with a specific focus on the timing of land use under recent and future climatic conditions. We apply the model to a case study in Northern Germany in which the conservation measures are extensive mowing regimes with specified mowing dates and frequencies and the conservation objectives are meadow-breeding bird species. We define cost-effectiveness as maximizing an ecological benefit indicator (here, effective habitat area generated for the target species, see section 3.1 for details) for a given (AES) budget constraint in a region that experiences climate change. We specifically model the impact of climate change on both the species and costs and consider two climate scenarios, RCP4.5 (moderate increase in greenhouse gas emissions) and RCP8.5 (large increase in greenhouse gas emissions). We determine the cost-effective set of conservation measures from a list of possible measures under recent (2000–2004) and future (2075–2079) climatic conditions.

We build on previous economic research on biodiversity conservation under climate change. So far, research has focused to a large extent on the cost-effectiveness of conservation measures and policy instruments. Gerling and Wätzold (2021) analyzed the cost-effectiveness of conservation policy instruments on a conceptual level, and Gerling et al. (2022a) examined cost-effective conservation measures under climate change for a specific species in a conservation planning context. Considering specific policy instruments, Schöttker and Wätzold (2022) investigated the cost-effectiveness of land purchase versus land lease, Huber et al. (2017) simulated the outcomes of several conservation measures of an AES, and Gerling et al. (2022b) examined cost-effectiveness gains through increased flexibility of conservation agencies for land purchase and sale. Given the prominence of uncertainty in the context of climate change, another focus of economic research on biodiversity conservation under climate change has been on different approaches of how to deal with risk (Mallory and Ando 2014; Shah et al. 2016; Drechsler et al. 2021). Further research addressed auctions as an incentive-based instrument for the provision of ecosystem services under climate change (Lewis and Polasky 2018) and people's willingness-to-pay for species migrating under climate change (Lundhede et al. 2014).

Conservation problem

Case study area

Our case study covers an area of 5,040 km^2 in the federal state Schleswig-Holstein in Northern Germany (Figure 1). The area has a maritime climate with a mean annual temperature of 8.3°C between 1961 and 1990. Variation between mean summer and winter temperatures is relatively small, as mean monthly temperatures range from around 0°C (in January) to 16°C (in June). Compared to most other areas in Germany, there are fewer "summer days" (defined as having a maximum temperature of at least 25°C) and fewer "frost days" (defined as having a minimum temperature of less than 0°C). Climate change is expected to lead to a moderate temperature rise in comparison with other areas of Germany, and precipitation is expected to increase in winter and spring and decrease in summer (DWD 2017).

The case study area is divided into climate cells of 12 × 12 km² (Figure 1). Furthermore, grassland areas that are used as meadows within the case study area are represented by grassland cells of 250 × 250 m². For each grassland cell, information such as the productivity of the land (measured by the German system of "grassland numbers" (Grünlandzahl[1])) and the presence of structural elements such as water bodies is available. Taking into account the land productivity allows for a spatial differentiation of biomass growth (influencing the opportunity costs of conservation), while information on biomass growth and additional information like the presence of structural elements allow for a spatial differentiation of conservation impacts at the spatial scale of grassland cells[2].

Target species

We consider a list of eight bird species that are threatened or likely to become threatened in the near future according to the red list (Knief et al. 2010): the black grouse (*Tetrao tetrix*), black-tailed godwit (*Limosa limosa*), common redshank (*Tringa totanus*), common snipe (*Gallinago gallinago*), meadow pipit (*Anthus pratensis*), northern lapwing (*Vanellus vanellus*), skylark (*Alauda arvensis*), and whinchat (*Saxicola rubetra*). All species are ground-breeding meadow birds but differ in their breeding period. Furthermore, the species differ in their habitat requirements such as humidity or grass length. We selected these species as they are of conservation interest (due to their red list status), and their habitat requirements are sensitive to the timing of agricultural land use. Moreover, both information on their breeding behavior in the recent past and on reactions to climatic changes were available. Details on the species' habitat requirements and breeding period can be found in Appendix A1.

Under climate change, the species may adapt phenologically by advancing the timing of typical life cycle events. Regarding bird species, one critical parameter is the beginning of the breeding period (Kluen et al. 2016). However, the phenological adaptations of different bird species are of different magnitude (Kluen et al. 2016). We therefore consider species-

[1]Grassland numbers are an overall indicator of productivity, consisting of various parameters such as humidity and soil characteristics (BMEL n.d.).

[2]The available biomass influences habitat quality as some species prefer longer grass, and others shorter grass (see Johst et al. 2015 for details).

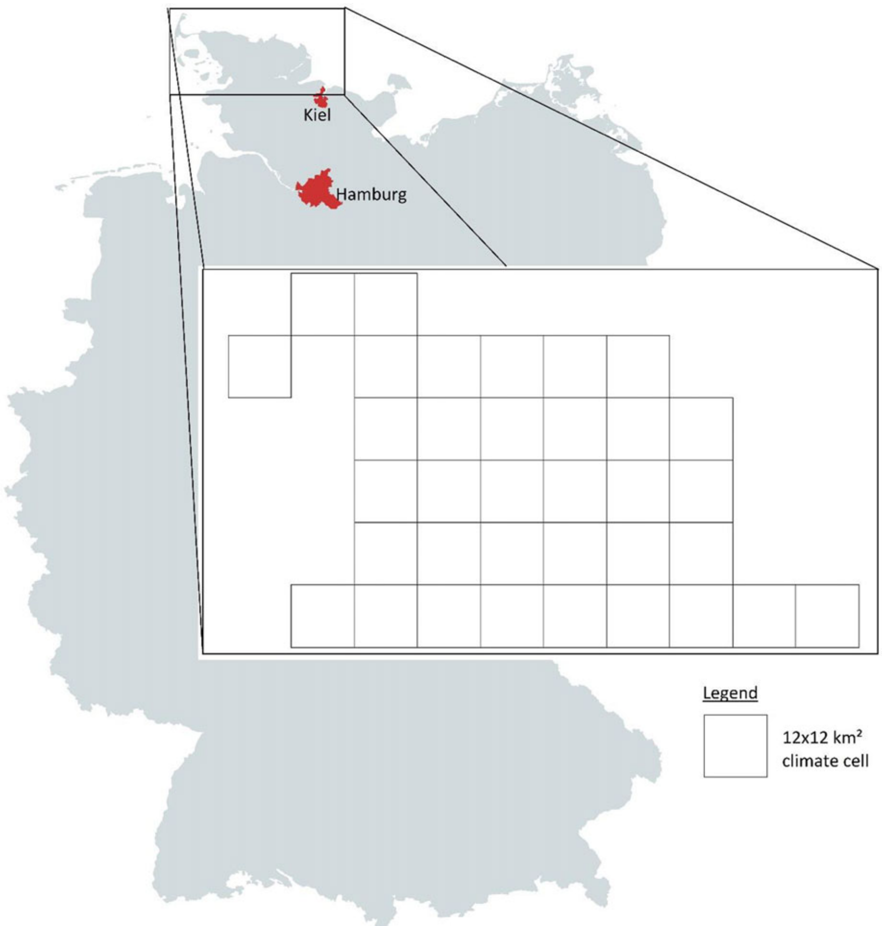

Figure 1. Illustration of the location of the case study area in the North of Germany and its division into $12 \times 12\,\text{km}^2$ climate cells. Map of Germany created with mapchart.net.

specific values regarding the timing and advance of egg deposition of the eight species in the ecological model.

AES framework: selection of conservation measures and budget

In the first period (2000–2004), we consider 11 conservation measures which are candidates for the conservation measures included in the cost-effective AES. These 11 measures were selected by determining the most cost-effective conservation measures for the species using DSS-Ecopay, an existing software-based decision support system to design cost-effective grassland AES to conserve birds and butterflies (Sturm et al. 2018). The measures differ in their frequency and timing of land use (Table 1). The timing of land use is given in quarter months (QM) by dividing each month into four equal parts consisting of approximately 7.5 days each.

Table 1. List of conservation measures. The measure name includes information on the timing and frequency of land use: for example, measure M19/6 allows for a first harvest in quarter month 19, followed by a break of 6 quarter months and a second harvest in quarter month 25

Measure name	Timing first harvest	Timing second harvest
Measures in both periods (2000–2004 and 2075–2079)		
M19/6	QM19 (3rd quarter of May)	QM25 (1st quarter of July)
M19/8	QM19 (3rd quarter of May)	QM27 (3rd quarter of July)
M20/6	QM20 (4th quarter of May)	QM26 (2nd quarter of July)
M21/6	QM21 (1st quarter of June)	QM27 (3rd quarter of July)
M22/6	QM22 (2nd quarter of June)	QM28 (4th quarter of July)
M23/6	QM23 (3rd quarter of June)	QM29 (1st quarter of August)
M24/6	QM24 (4th quarter of June)	QM30 (2nd quarter of August)
M25/6	QM25 (1st quarter of July)	QM31 (3rd quarter of August)
M26/0	QM26 (2nd quarter of July)	None
M27/0	QM27 (3rd quarter of July)	None
M28/0	QM28 (4th quarter of July)	None
Additional measures in period 2 (2075–2079)		
M17/6*	QM17 (1st quarter of May)	QM23 (3rd quarter of June)
M17/8*	QM17 (1st quarter of May)	QM25 (1st quarter of July)
M18/6*	QM18 (2nd quarter of May)	QM24 (4th quarter of June)
M18/8*	QM18 (2nd quarter of May)	QM26 (2nd quarter of July)

To account for possible phenological adaptations, we consider four additional conservation measures in the second period (2075–2079), M17/6, M17/8, M18/6, and M18/8, which represent shifts of the initially earliest measures (M19/6 and M19/8) by one and two quarter months. We thus have a list of 15 possible conservation measures for the second period.

The budget for each 5-year period is set to 3,725,000€, which would allow for approximately 15% of the grassland area to be conserved if on each grassland cell the most cost-effective conservation measure was implemented. We chose this value as in Schleswig-Holstein, 15% of permanent grasslands were managed with biodiversity-enhancing conservation measures in 2014–2020 (Sander et al. 2019) and 15% is also sufficiently large to have a clear visibility of any relevant effects.

Climate-ecological-economic model

Overview of the CEE model

We adapt the CEE model by Gerling et al. (2022a), which focuses on climate change impacts in a conservation planning context for a grasshopper species, and combine it with an ecological-economic modelling procedure to design cost-effective AES to conserve grassland birds developed by some of the authors in previous work (Wätzold et al. 2016) in order to model an AES context and the mowing impact on bird species. As nearly

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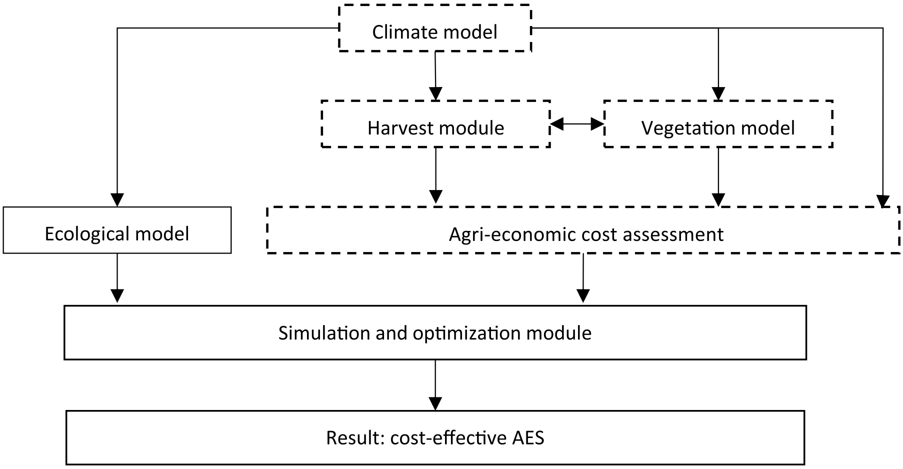

Figure 2. Structure of the CEE model (adapted from Gerling et al. 2022a). Boxes with dashed borders are taken from Gerling et al. (2022a), and boxes with solid lines represent modifications.

all components of the applied CEE model are described in other papers, we restrict ourselves here to providing an overview of the model (Figure 2), explaining how we take into account climate change in the ecological-economic modelling procedure (Johst et al. 2015; Wätzold et al. 2016) and otherwise referring the interested reader to the literature. Keuler et al. (2016) provides detailed information on the climate model, the vegetation model is based on Schippers and Kropff (2001), and details on the harvest module and the agri-economic cost assessment can be found in Gerling et al. (2020). The ecological model of the modelling procedure is explained in Johst et al. (2015), and the simulation and optimization module in Wätzold et al. (2016) and Sturm et al. (2018) (see also Appendix A2).

The basis of the CEE model is the climate model, which generates high-resolution climate projections of parameters like temperature and precipitation using the regional climate model COSMO-CLM (Rockel et al. 2008; Früh et al. 2016). Climate data is available at a spatial scale of $12 \times 12\,\text{km}^2$ climate cells on a daily basis. We examine two scenarios, which differ in the emission pathways: a medium-emission scenario (RCP4.5) and a high-emission scenario (RCP8.5) (IPCC 2014). We do not consider a low-emission scenario as given current emission reductions, reaching a low-emission scenario seems increasingly unlikely (Sanderson et al. 2016). Climate data is used as an input for the vegetation model, which is a simplified model of grass growth based on Schippers and Kropff (2001). The vegetation model provides input to the harvest module and the agri-economic assessment and is needed to determine the costs of conservation measures. Grass growth is determined at the spatial scale of $250 \times 250\,\text{m}^2$ grassland cells.

We then consider the business-as-usual (BAU) land use (i.e., the land use in the absence of an AES) and a list of alternative conservation measures defined by their timing of land use (cp. Table 1). Based on climatic conditions and grass growth, the harvest module estimates the yield-maximizing timing of harvest for the BAU land use and the different conservation measures on each grassland cell. However, the yield-maximizing timing of harvest may not be profit-maximizing. For example, while highly productive grassland may be harvested up to four times, the variable costs may exceed the value of the fourth harvest on less productive grassland.

We consider this in the agri-economic cost assessment, which determines the profit-maximizing timing of harvest for each grassland cell. Given this timing, the second output of the agri-economic cost assessment is grassland cell-specific cost estimates of each conservation measure for both periods (2000–2004 and 2075–2079), that is, the differences in profit between the BAU land use and the conservation measures. We consider changes in variable costs (such as the necessary machinery) and changes in the value of the yield of the BAU land use and the conservation measure. Changes in the yield value depend on the quantity and quality of the harvest (Mewes et al. 2015) and may be impacted by changing climatic conditions (Ray et al. 2019; Gerling et al. 2020; Lachaud et al. 2021). Moreover, we consider the impact of extreme events. In particular, changes in precipitation patterns may lead to increased frequency of flooding before the first harvest as precipitation shifts from summer towards spring (DWD 2017). However, when a meadow is flooded for an extended period of time, the quality of the harvest decreases rapidly (Gerling et al. 2020).

The ecological model builds on previous research (Johst et al. 2015) regarding the impact of differently timed conservation measures on meadow bird species with differing habitat requirements. The model is the basis for the assessment of the impact of conservation measures on birds in the software-based decision support system DSS-Ecopay (Sturm et al. 2018). In the ecological model, we determine the local habitat quality generated by each conservation measure for each species and for each grassland cell. The local habitat quality is given as a value between 0 and 1, with 0 representing very low habitat quality (i.e., reproduction is impossible) and 1 representing very high quality (ideal conditions). To determine the local habitat quality, we consider grassland-cell-specific conditions which are independent of the timing of egg deposition (such as the presence of structural elements and the grassland type) and factors that depend on the timing of egg deposition (such as mortality caused by mowing machines). We then sum up the local habitat qualities of all grassland cells in order to determine the total effective habitat area generated in the case study region. This value is thus an indicator of the overall conservation impact of a conservation measure on a species. DSS-Ecopay was used to determine the total effective habitat area.

The simulation and optimization module follows the same logic as the algorithm from Wätzold et al. (2016). The module is applied to the data sets from the ecological model and the agri-economic cost assessment. It combines information from the agri-economic cost assessment and the ecological model in order to estimate the expected conservation impact and the costs of each conservation measure for each grassland cell under recent (2000–2004) and future (2075–2079) climatic conditions. Using simulated annealing, the optimization tries different payments for each measure in a stepwise process in order to maximize the ecological outcome for a given budget constraint. For each step, the algorithm simulates the farmers' profit-maximizing decision on which measure to apply considering the payments for the different measures and their costs. The ecological outcome is measured as the sum of the effective habitat areas generated for all species in the landscape, implying that each species is given the same weight.

The final output of the CEE model is the cost-effective AES consisting of a set of conservation measures and their respective payments for the case study area under recent (2000–2004) and future (2075–2079) climatic conditions. We take a period from the recent past (rather than current conditions), as the underlying ecological-economic model (Wätzold et al. 2016) was parametrized based on data and studies from this time. The second period was chosen in order to be able to observe the effects of long-term climate change and due to data availability.

Table 2. Species-specific phenological adaptations of egg deposition. Adaptations highlighted by an asterisk (*) refer to approximations based on changes in the arrival date

Species	Phenological adaptation (change in egg deposition*)	Relevant climatic criterion	Data source
Black grouse (*Tetrao tetrix*)	−1.1 days	Per 1°C April temperature	Ludwig et al. 2006
Black-tailed godwit (*Limosa limosa*)	±0 days		Schroeder et al. 2012, Kentie et al. 2018
Common redshank (*Tringa totanus*)	−1.8 days*	Per 1°C April temperature	Gunnarsson & Tómasson 2011
Common snipe (*Gallinago gallinago*)	−3.7 days*	Per 1°C April temperature	Gunnarsson & Tómasson 2011
Meadow pipit (*Anthus pratensis*)	−1.0 days*	Per 1°C April temperature	Gunnarsson & Tómasson 2011
Northern lapwing (*Vanellus vanellus*)	−3.0 days	Per 1°C spring (March to May) temperature	Kluen et al. 2016
Skylark (*Alauda arvensis*)	−3.4 days*	Per 1°C March	Askeyev et al. 2009
Whinchat (*Saxicola rubetra*)	−1.6 days	Per 1°C spring (March to May) temperature	Kluen et al. 2016

Phenological adaptations in the ecological model

In order to examine the impact of climate change on the bird species, we consider phenological adaptations of the species in terms of the timing of egg deposition. Importantly, the species react differently to climatic changes. Table 2 summarizes the expected adaptations for each species based on values published in the literature. In some cases, values are only available regarding changes in the arrival date of migratory birds. In these cases, we take the adaptation of the arrival date as an indicator for the adaptation of egg deposition.

Results

In the RCP4.5 scenario, climate change has only minor impacts on the cost-effectiveness of the AES: in this scenario, the cost-effective AES consists of the same conservation measure in both periods (M27/0), but the payment is increased from 745€/ha to 800€/ha. Furthermore, the species' phenological adaptations result in an increase in total effective habitat area generated. We therefore focus on the results of the RCP8.5 scenario here and present detailed results of the RCP4.5 scenario in Appendix A3.

In the RCP8.5 scenario, the cost-effective AES consists of only one measure in each period. While in period 1, the two-cut measure M25/6 is included, in period 2 only one cut is allowed (M28/0). The payment of M28/0 is higher (at 587€/ha) than that of M25/6 (374€/ha) as opportunity costs of this measure are higher. The increase in payment size is due to a combination of a less suitable timing (harvesting for the first time in QM28

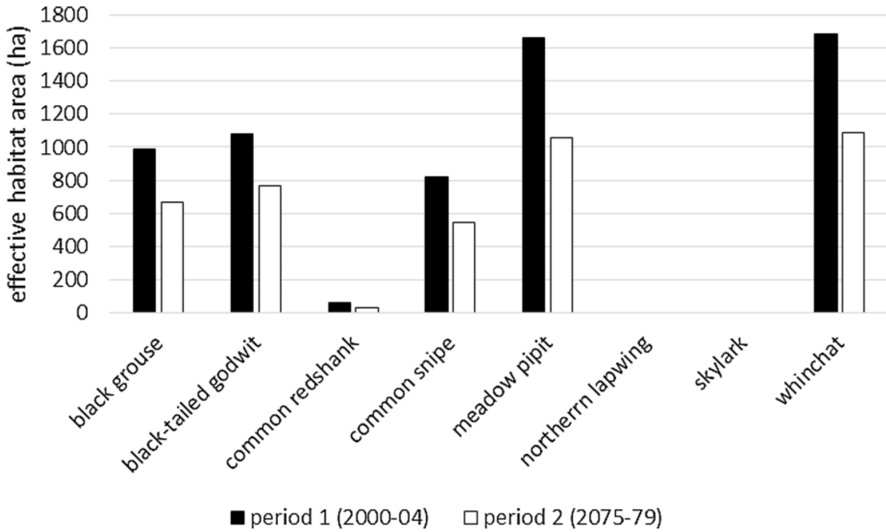

Figure 3. Effective habitat area (ha) generated for each species by each measure in period 1 (2000–2004) and 2 (2075–2079) (RCP8.5).

is very late in comparison with the BAU land use) and a more restrictive land use, as only a single harvest is permitted.

Given that the payment per hectare is higher for the measure selected in period 2, the overall area conserved is smaller by 34%. Figure 3 shows our indicator for the conservation success of the AES, the effective habitat area for each species. Out of the eight species considered in the optimization, six species are conserved in both periods. However, the effective habitat areas for these species in period 2 is smaller than in period 1.

Figure 4 shows the relative losses in effective habitat area overall and for each species. Whereas 34% of the total effective habitat area are lost in the second period, some species experience larger losses than others. In particular the common redshank loses almost half its original habitat area, while the black-tailed godwit only loses 29%. This is due to the different timing of the reproduction phases of the two species, their habitat requirements and/or their phenological adaptations (see Appendix A5 for details).

Figure 5 shows the spatial distribution of conservation sites in the two periods and the relative losses between the two periods. It can be seen that while in period 1, conservation activities occur more evenly throughout the landscape, they concentrate on fewer climate cells in the center of the case study area in period 2. In particular, climate cells that initially include only few conserved areas are lost (almost) completely in period 2.

In order to gain a better understanding of the results, we additionally examine whether the change in the selected measure is driven by cost changes or by the species' adaptations. Regarding costs, Figure 6 shows that the marginal costs of conserving an additional grassland cell with measure M25/6 are markedly higher in period 2 than in period 1. In period 1, this measure is the lowest cost measure (see Appendix A4 for details). Considering measure M28/0, costs in period 2 are only slightly higher than in period 1. Most conservation measures generate higher costs in period 2 than in period 1. However, cost changes differ strongly between measures (see Appendix A4). The reason for these differences lies in the occurrence of extreme events, in particular flooding. In period 2, measure M28/0 is a

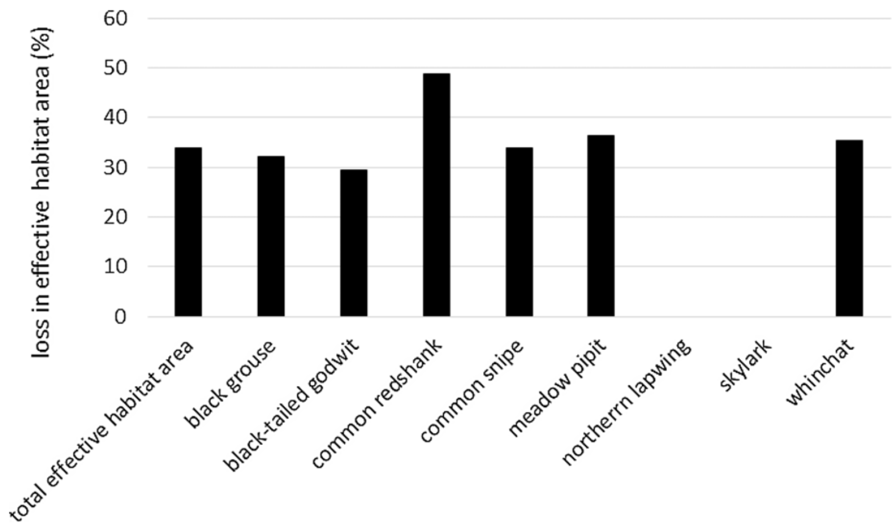

Figure 4. Loss in total effective habitat area (%) and in effective habitat area (%) generated for each species between period 1 (2000–2004) and 2 (2075–2079) (RCP8.5).

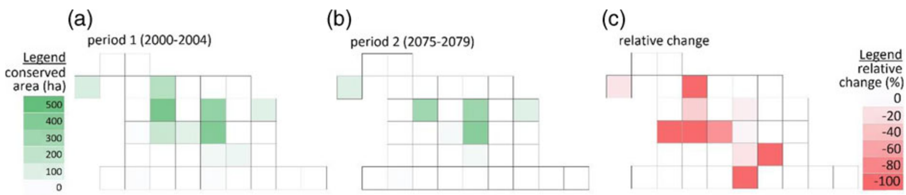

Figure 5. Spatial distribution of conservation sites in periods 1 (a), period 2 (b), and relative losses between the two periods (c). Colors represent a continuous scale.

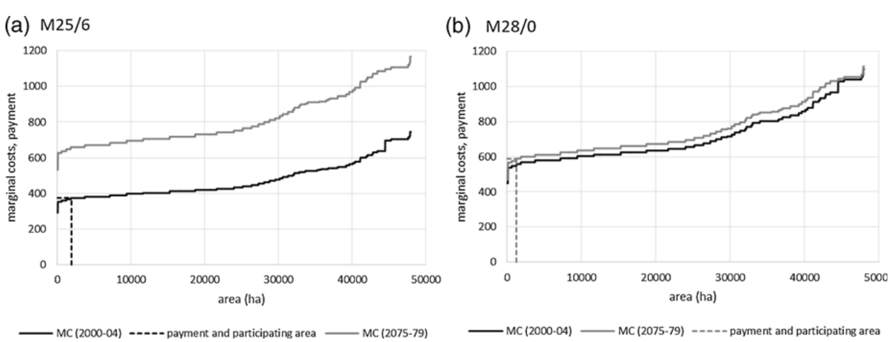

Figure 6. Marginal costs of conservation measures M25/6 and M28/0 in period 1 (2000–2004) and 2 (2075–2079) (RCP8.5).

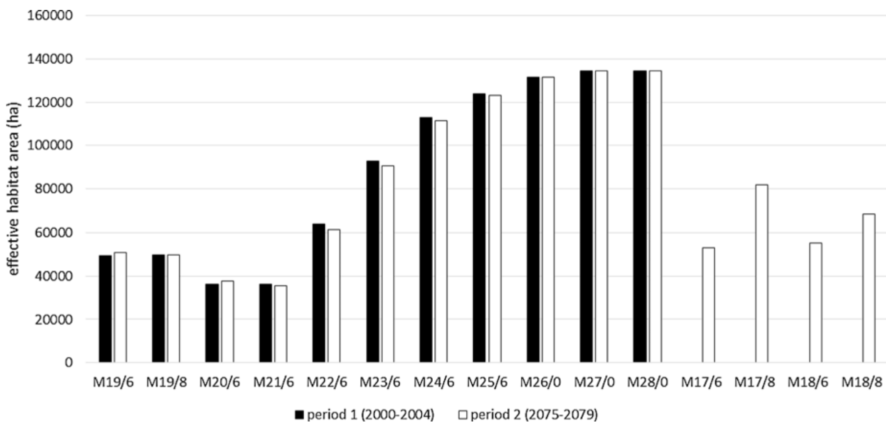

Figure 7. Total effective habitat area if each conservation measure was implemented on all sites in period 1 (2000–2004) and 2 (2075–2079) (RCP8.5).

measure of medium costs and has the lowest costs of those allowing only a single harvest. Moreover, the measures allowing only a single harvest have comparatively low costs in the RCP8.5 scenario (see Appendix A4 for details). Further analyses show that cost changes are relatively homogeneous throughout the landscape (Appendix A4). Overall, cost analyses thus support the shift from measure M25/6 to M28/0: while measure M25/6 is the lowest cost measure in period 1, it has higher costs in period 2. Measure M28/0, which is chosen in period 2, has medium costs but low costs in comparison with other measures that allow only a single harvest.

We now consider whether ecological outcomes also support the shift from measure M25/6 towards measure M28/0. Figure 7 shows the ecological benefit per measure for both periods. It can be seen that the differences between the two periods are small and spatial analyses show that differences over time remain small throughout the landscape (Appendix A4). However, early measures (with a first harvest until quarter month 20) have a higher ecological benefit in period 2 than in period 1, while measures with a medium timing (with a first harvest between quarter months 21–25) have a higher ecological benefit in period 1. This is due to the phenological adaptations of the species. The measures allowing only a single harvest have a very late cut (starting from quarter month 26), and their impact on the breeding period for the species is equal in both periods (see Appendix A5 for details).

Moreover, the measures allowing only a single, late harvest have the largest ecological benefits. In particular, measure M28/0 (which is chosen in period 2) has the highest ecological benefit, while it also has the lowest costs out of all conservation measures allowing only a single harvest.

In summary, in period 1, the measure with lowest costs and medium-high benefits is the cost-effective one, whereas in period 2, a measure with medium costs but the highest benefit is chosen. The results are thus triggered by an interplay of economic and ecological parameters, and in particular by the impact of extreme events on costs and the impact of the species' phenological adaptations on species' benefits from a conservation measure with a fixed timing of harvest. Extreme events play a smaller role in the RCP4.5 scenario, and hence, there are no changes in the conservation measures selected for the cost-effective AES for the two periods.

Discussion and conclusion

We developed a CEE model to examine the cost-effectiveness of an AES and its necessary adaptations under climate change. To the best of our knowledge, this is the first model investigating the cost-effective design of AES for biodiversity conservation under climate change. A further novelty is that the focus of our paper is on the timing of the conservation measure, whereas most other work concentrates on spatial adaptations. We applied the model to determine the cost-effective AES for a set of meadow birds in Northern Germany. The model considers the impact of climate change on both the species and costs of conservation. Our results show that while under the RCP4.5 scenario, the cost-effective AES changes only in terms of the payment size, in the RCP8.5 scenario the cost-effective AES also changes in terms of the conservation measure included in the AES.

This change occurs due to the impact of climate change on both conservation costs and benefits. Regarding costs, we find a high variability of conservation costs due to extreme events (inundations) to play a key role in causing relative cost advantages for the selected conservation measure under climate change. Moreover, this conservation measure also provides large ecological benefits due to the late timing of land use, and the phenological adaptations of the species further increase the relative benefit of this measure compared to other measures of similar costs. The change in conservation measures in the cost-effective AES may therefore be explained by the impact of extreme events on conservation costs and the species' phenological adaptations to climate change. Apart from the specific results for the case study, our research also allows us to derive two general insights and policy recommendations regarding the design of AES under climate change.

First, our results provide an indication that conservation measures need to be adapted to climate change with respect to the temporal dimension. Current policy documents such as the Strategic Plan for Responding to Accelerating Climate Change (US Fish and Wildlife Service 2010), the EU Biodiversity Strategy for 2030 (The European Commission 2021), and the German Adaptation Strategy to Climate Change (Die Bundesregierung 2008) focus on the spatial dimension, emphasizing the need to adapt the location of conservation sites due to species' range shifts. However, the need to also adapt the temporal restrictions of conservation measures is so far rarely considered in policy strategies. Our results show that neglecting the temporal dimension reduces the cost-effectiveness of conservation given climatic changes. This is relevant for any species that would be negatively affected by mechanical land use directly – apart from ground-breeding meadow birds, this may also include species such as butterflies (Johst et al. 2015) and grasshoppers (Leins et al. 2021) among others. Additionally, the timing of land use may influence species indirectly by creating certain habitat types (Johst et al. 2015), ensuring the availability of feeding plants (e.g., the availability of milkweed for monarch butterflies (Thogmartin et al. 2017)), or providing suitable habitat during migration phases (e.g., for migrating shorebirds along the Pacific Flyway in California (Golet et al. 2018)). One simple way of adapting conservation measures automatically may be by defining their timing phenologically (e.g., in relation to the phenological beginning of spring), rather than setting fixed dates. Gerling et al. (2022a) have shown that such measures may remain cost-effective under changing climatic conditions for the conservation of the large marsh grasshopper in Northern Germany, but whether this finding can be generalized requires further analysis.

Second, our results highlight that the increase of extreme events under climate change needs to be considered in the design of cost-effective AES. In our case, extreme events, specifically flooding, have a substantial impact on costs as the harvest during certain periods of the year becomes less valuable or unusable. Previous research has considered the impact of climate change on opportunity costs due to changes in the vegetation period

(Huber et al. 2017), while our results show that extreme events may also play an important role. However, climate projections only inform about the increasing probability of the occurrence of extreme events, while the exact years in which they occur are uncertain. One way of dealing with this uncertainty are robustness analyses, which allow to identify robust conservation strategies given uncertain climate change (Mallory and Ando 2014; Shah et al. 2016; Drechsler et al. 2021). In this way, one could identify conservation measures which are relatively cost-effective even in years of extreme events, rather than choosing conservation measures with the highest expected outcomes, which, however, may have a very low cost-effectiveness in certain years. This would reduce the variability of ecological outcomes and/or costs over time. The important influence of extreme events on the cost-effective design of the AES in our case study thus provides further indications for including robustness considerations in the design of conservation schemes.

In order to simplify complex processes and due to data limitations, we had to make some assumptions which require a discussion. Regarding the ecological model, we had to reduce the complexity of the possible adaptations of the species to climate change by not considering phenological changes in life cycle parameters driven by climate change other than the beginning of the breeding period (e.g., changes in the reproductive success of birds due to a mismatch between the hatching timing and peak nutritive quality of plants (Reséndiz-Infante and Gauthier 2020)). Given that we focus on the desynchronizations between the timing of harvest and the species' breeding period, we expect our results to nonetheless highlight valuable trends. Further simplifications within the ecological model include the assumptions that changes to the arrival date are an indicator for the timing of egg deposition and that estimates from studies from a range of countries also hold for Northern Germany.

Furthermore, we simplified the interactions between the ecological model and other submodels to limit computation time: local humidity and grass length influence the suitability of a grassland cell for the species, and we consider spatial differences in these parameters between different grassland cells. However, climate change may also influence these parameters over time, for example, by changing the dynamics of grass growth (and thus, grass length at any chosen point of time) or humidity due to changes in precipitation patterns. While we consider climate-induced changes in local humidity and grass growth dynamics in the agri-economic cost assessment, we exclude it in the ecological model to limit the dependencies between the ecological model and the climate and vegetation models in order to reduce computation time. This implies that we take these parameters as a general indicator of the suitability of a grassland cell and assume that the values are stable over time.

Finally, the impact of climate change on conservation costs and species is uncertain. For example, the uncertain impact on species is visible by different studies reporting different expected phenological adaptations for the same species. Regarding our target species specifically, we expect the black-tailed godwit to not adapt its timing of egg deposition based on two studies (Schroeder et al. 2012; Kentie et al. 2018). However, Gunnarson and Tómasson (2011) did find phenological adaptations of the arrival date.

Despite these limitations, we believe our CEE model to be a useful approach to obtain an understanding of necessary adaptations for cost-effective AES under climate change. However, when translating these results into concrete recommendations for the adaptation of actual AES, the underlying assumptions and uncertainties need to be considered. More detailed recommendations that go beyond the general recommendations drawn from this research would therefore require a deeper understanding of the impacts of climate change on the target species (see e.g., Gerling et al. (2022a) on the large marsh grasshopper) and the development of recommendations that explicitly take into account uncertainty (Drechsler et al. 2021).

Our research has shown how CEE modelling may be used for the analysis of AES under climate change and has highlighted the need to adapt the timing of conservation measures to climate change to maintain the cost-effectiveness of AES. Given the prominence of PES or AES, and the large amount of public resources spent on such schemes, we believe further research on the "climate-smart" design of AES to be highly valuable.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/age.2023.4

Data Availability Statement. The following data underlying the article is available:
Regarding the climate model, the data underlying the article are available at https://esgf-data.dkrz.de/projects/esgf-dkrz/. The code for the climate model requires a licensing agreement with the DWD or membership in the CLM community. This is possible after signing a community agreement.

Regarding the harvest module and agri-economic cost assessment, the data underlying the article are available at http://www.inf.fu-berlin.de/DSS-Ecopay/software_eng.html (files "Schleswig_Holstein_Dateien_fuer_Ecopay.zip"). The code for the two models can be cloned through the command line with git clone at git@85.214.153.232:ecoclimb.git.

Regarding the ecological model, the database including the bird species and the decision support system DSS-Ecopay are available from the DSS-Ecopay website: http://www.inf.fu-berlin.de/DSS-Ecopay/software_eng.html

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References

Alagador, D., J.O. Cerdeira, and M.B. Aráujo 2014. "Shifting Protected Areas: Scheduling Spatial Priorities under Climate Change." *Journal of Applied Ecology* **52651**(3): 703–713.

Alagador, D., J.O. Cerdeira, and M.B. Aráujo 2016. "Climate Change, Species Range Shifts and Dispersal Corridors: An Evaluation of Spatial Conservation Models." *Methods in Ecology and Evolution* **7**(7): 853–866.

Allen, M.C., J.L. Lockwood, and J. Burger 2021. "Finding Clarity in Ecological Outcomes Using Empirical Integrated Social–Ecological Systems: A Case Study of Agriculture-Dependent Grassland Birds." *Journal of Applied Ecology* **58**(3): 528–538.

Ando, A.M. and M.L. Mallory 2012. "Optimal Portfolio Design to Reduce Climate-Related Conservation Uncertainty in the Prairie Pothole Region." *PNAS* **109**(17): 6484–6489.

Armsworth, P.R., S. Acs, M. Dallimer, K.J. Gaston, N. Hanley, and P. Wilson 2012. "The Cost of Policy Simplification in Conservation Incentive Programs." *Ecology Letters* **15**(5): 406–414.

Askeyev, O.V., T.H. Sparks, and I.V. Askeyev 2009. "Earliest Recorded Tatarstan Skylark in 2008: Non-linear Response to Temperature Suggests Advances in Arrival Dates May Accelerate." *Climate Research* **38**: 189–192.

Bartkowski, B., N. Droste, M. Ließ, W. Sidemo-Holm, U. Weller, and M.V. Brady 2021. "Payments by Modelled Results: A Novel Design for Agri-environmental Schemes." *Land Use Policy* **102**: 105230.

BMEL (n.d.) '100er Boden—bestbewerteter Boden in Deutschland'. Available at https://www.bmel.de/DE/themen/landwirtschaft/pflanzenbau/bodenschutz/boden100er.html. (Accessed 15 May 2020).

Chakrabarti, A., L. Chase, A.M. Strong, and S.K. Swallow 2019. "Making Markets for Private Provision of Ecosystem Services: The Bobolink Project." *Ecosystem Services* **37**: 100936.

Cole, M.A., R.J.R. Elliott, and E. Strobl 2021. "Biodiversity and Economic Land Use." *Land Economics* **97**(2): 281–304.

Cong, W., Y.L. Dupont, K. Søegaard, and J. Eriksen 2020. "Optimizing Yield and Flower Resources for Pollinators in Intensively Managed Multi-species Grasslands." *Agriculture, Ecosystems & Environment* **302**: 107062.

Cui, X., and W. Xie 2021. "Adapting Agriculture to Climate Change through Growing Season Adjustments: Evidence from Corn in China." *American Journal of Agricultural Economics* **104**(1): 249–272.

Dakpo, K.H., L. Latruffe, Y. Desjeux, and P. Jeanneaux 2021. "Modeling Heterogeneous Technologies in the Presence of Sample Selection: The Case of Dairy Farms and the Adoption of Agri-environmental Schemes in France. *Agricultural Economics* **53**(3): 422–438.

Dasgupta, P. 2021. *The Economics of Biodiversity: The Dasgupta Review*. London: HM Treasury.

Die Bundesregierung. 2008. *Deutsche Anpassungsstrategie an den Klimawandel*. Available at https://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/das_gesamt_bf.pdf [05.08.2021].

Drechsler, M., C. Gerling, K. Keuler, J. Leins, A. Sturm, and F. Wätzold 2021. "A Quantitative Approach for the Design of Robust and Cost-effective Conservation Policies under Uncertain Climate Change: The Case of Grasshopper Conservation in Schleswig-Holstein, Germany." *Journal of Environmental Management* **296**: 113201.

Drechsler, M., F. Wätzold, and V. Grimm 2022. "The Hitchhiker's Guide to Generic Ecological-economic Modelling of Land-use-Based Biodiversity Conservation Policies." *Ecological Modelling* **465**: 109861.

Duke, J.M., S.J. Dundas, R.J. Johnston, and K.D. Messer 2014. "Prioritizing Payment for Environmental Services: Using Nonmarket Benefits and Costs for Optimal Selection." *Ecological Economics* **105**: 319–329.

Duke, J.M., S.J. Dundas, and K.D. Messer 2013. "Cost-effective Conservation Planning: Lessons from Economics." *Journal of Environmental Management* **125**: 126–133.

Duke, J.M., R.J. Johnston, A.L. Shober, and Z. Liu 2022. "Improving Targeting of Farmers for Enrollment in Agri-environmental Programs." *Applied Economic Perspectives and Policy* (early view).

DWD. 2017. *Klimareport Schleswig-Holstein*. Offenbach am Main, Deutschland: Deutscher Wetterdienst.

Früh, B., Will, A., and Castro, C.L. (Eds) 2016. "Recent Developments in Regional Climate Modelling with COSMO-CLM." *Meteorologische Zeitschrift* **25**(2): 119–120.

Gerling, C., M. Drechsler, J. Leins, K. Keuler, K. Radtke, B. Schulz, A. Sturm, and F. Wätzold 2022a. "Combining Ecological-economic Modelling and Climate Science for the Cost-effective Spatio-temporal Allocation of Conservation Measures in the Face of Climate Change." *Q Open* **2**(1): qoac004.

Gerling, C., O. Schöttker, and J. Hearne 2022b. "Irreversible and partly reversible investments in the optimal reserve design problem: the role of flexibility under climate change." MRPA Paper No. 112089. Available at https://mpra.ub.uni-muenchen.de/112089/1/MPRA_paper

Gerling, C., A. Sturm, and F. Wätzold 2020. "The impact of climate change on the profit-maximising timing of grassland use and conservation costs." MPRA. Available at https://mpra.ub.uni-muenchen.de/105597/ [01.02.2021].

Gerling, C., and F. Wätzold 2021. "An Economic Evaluation Framework for Land-use-based Conservation Policy Instruments in a Changing Climate." *Conservation Biology* **35**(3): 824–833.

Golet, G.H., C. Low, S. Avery, K. Andrews, C.J. McColl, R. Laney, and M.D. Reynolds 2018. "Using Ricelands to Provide Temporary Shorebird Habitat During Migration." *Ecological Applications* **28**(2): 409–426.

Gunnarsson, T.G., and G. Tómasson 2011. "Flexibility in Spring Arrival of Migratory Birds at Northern Latitudes under Rapid Temperature Changes." *Bird Study* **58**(1): 1–12.

Huber, R., R. Snell, F. Monin, S.H. Brunner, D. Schmatz, and R. Finger 2017. "Interaction Effects of Targeted Agri-environmental Payments on Non-marketed Goods and Services under Climate Change in a Mountain Region." *Land Use Policy* **66**: 49–60.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Jiang, Y., and S.K. Swallow 2017. "Impact Fees Coupled With Conservation Payments to Sustain Ecosystem Structure: A Conceptual and Numerical Application at the Urban-Rural Fringe." *Ecological Economics* **136**: 136–147.

Johst, K., M. Drechsler, M. Mewes, A. Sturm, and F. Wätzold 2015. "A Novel Modeling Approach to Evaluate the Ecological Effects of Timing and Location of Grassland Conservation Measures." *Biological Conservation* **182**(02/2015): 44–52.

Kentie, R., T. Coulson, J.C.E.W. Hooijmeijer, R.A. Howison, A.H.J. Loonstra, M.A. Verhoeven, C. Both, and T. Piersma 2018. "Warming Springs and Habitat Alteration Interact to Impact Timing of Breeding and Population Dynamics in a Migratory Bird." *Global Change Biology* **24**(11): 5292–5303.

Keuler, K., K. Radtke, S. Kotlarski, and D. Lüthi 2016. "Regional Climate Change over Europe in COSMO-CLM: Influence of Emission Scenario and Driving Global Model." *Meteorologische Zeitschrift* **25**(2): 121–136.

Khanna, M., S.M. Swinton, and K.D. Messer 2018. "Sustaining our Natural Resources in the Face of Increasing Societal Demands on Agriculture: Directions for Future Research." *Applied Economic Perspectives and Policy* **40**(1): 38–59.

Kleijn, D., R.A. Baquero, Y. Clough, M. Díaz, J. De Esteban, F. Fernández, D. Gabriel, F. Herzog, A. Holzschuh, R. Jöhl, E. Knop, A. Kruess, E.J.P. Marshall, I. Steffan-Dewenter, T. Tscharntke, J. Verhulst, T.M. West, and J.L. Yela 2006. "Mixed Biodiversity Benefits of Agri-environment Schemes in Five European Countries." *Ecology Letters* **9**(3): 243–254.

Kluen, E., R. Nousiainen, and A. Lehikoinen 2016. "Breeding Phenological Response to Spring Weather Conditions in Common Finnish Birds: Resident Species Respond Stronger than Migratory Species." *Journal of Avian Biology* **48**(5): 611–619.

Knief, W., R.K. Berndt, B. Hälterlein, K. Jeromin, J.J. Kieckbusch, and B. Koop 2010. *Die Brutvögel Schleswig-Holsteins: Rote Liste*. Kiel: Ministerium für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (MLUR). Available at https://www.schleswig-holstein.de/DE/Fachinhalte/A/artenschutz/Downloads/rl_voegel_2010_pdf.pdf?__blob=publicationFile&v=1 (accessed 05.05.2022).

Lachaud, M.A., B.E. Bravo-Ureta, and C.E. Ludena 2021. "Economic Effects of Climate Change on Agricultural Production and Productivity in Latin America and the Caribbean (LAC)." *Agricultural Economics* **53**(2): 321–332.

Leins, J.A., T. Banitz, V. Grimm, and M. Drechsler 2021. "High-resolution PVA along Large Environmental Gradients to Model the Combined Effects of Climate Change and Land Use Timing: Lessons from the Large Marsh Grasshopper." *Ecological Modelling* **440**: 109355.

Lewis, D.J., A.J. Plantinga, E. Nelson, and S. Polasky 2011. "The Efficiency of Voluntary Incentive Policies for Preventing Biodiversity Loss." *Resource and Energy Economics* **33**(1): 192–211.

Lewis, D.J., and S. Polasky 2018. "An Auction Mechanism for the Optimal Provision of Ecosystem Services under Climate Change." *Journal of Environmental Economics and Management* **92**: 20–34.

Lichtenberg, E. 2021. "Additionality in Payment for Ecosystem Services Programs: Agricultural Conservation Subsidies in Maryland." *Land Economics* **97**(2): 305–320.

Ludwig, G.X., R.V. Alatalo, P. Helle, H. Lindén, J. Lindström, and H. Siitari 2006. "Short- and long-term Population Dynamical Consequences of Asymmetric Climate Change in Black Grouse." *Proceedings of the Royal Society of Birds* **273**(1597): 2009–2016.

Lundhede, T.H., J.B. Jacobsen, N. Hanley, J. Fjeldså, C. Rahbek, N. Strange, and T.B. Jellesmark 2014. "Public Support for Conserving Bird Species Runs Counter to Climate Change Impacts on Their Distributions." *PLOS ONE* **9**(7): e101281.

Mallory, M.L., and A.W. Ando 2014. "Implementing Efficient Conservation Portfolio Design." *Resource and Energy Economics* **38**: 1–18.

Mennig, P., and J. Sauer 2020. "The Impact of Agri-environment Schemes on Farm Productivity: A DID-matching Approach." *European Review of Agricultural Economics* **47**(3): 1045–1093.

Messer, K.D. 2006. "The Conservation Benefits of Cost-effective Land Acquisition: A Case Study in Maryland." *Journal of Environmental Management* **79**(3): 305–315.

Mewes, M., M. Drechsler, K. Johst, A. Sturm, and F. Wätzold 2015. "A Systematic Approach for Assessing Spatially and Temporally Differentiated Opportunity Costs of Biodiversity Conservation Measures in Grasslands." *Agricultural Systems* **137**: 76–88.

Ohl, C., M. Drechsler, K. Johst, and F. Wätzold 2008. "Compensation Payments for Habitat Heterogeneity: Existence, Efficiency, and Fairness Considerations." *Ecological Economics* **67**(2): 162–174.

Oliver, T.H., R.J. Smithers, C.M. Beale, and K. Watts 2016. "Are Existing Biodiversity Conservation Strategies Appropriate in a Changing Climate?" *Biological Conservation* **193**: 17–26.

**Pecl, G.T., M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C.

McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, and S.E. Williams 2017. "Biodiversity Redistribution under Climate Change: Impacts on Ecosystems and Human Well-being." *Science* **355**(6332): eaai9214.

Perlut, N.G., A.M. Strong, and T.J. Alexander 2011. "A Model for Integrating Wildlife Science andAgri-Environmental Policy in the Conservation of Declining Species." *The Journal of Wildlife Management* **75**(7): 1657–1663.

Polasky, S., E. Nelson, D. Pennington, and K.A. Johnson 2011. "The Impact of Land-Use Change on Ecosystem Services, Biodiversity and Returns to Landowners: A Case Study in the State of Minnesota." *Environmental and Resource Economics* **48**: 219–242.

Rashford, B.S., R.M. Adams, J. Wu, R.A. Voldseth, G.R. Guntenspergen, B. Werner, and W.C. Johnson 2016. "Impacts of Climate Change on Land-use and Wetland Productivity in the Prairie Pothole Region of North America." *Regional Environmental Change* **16**: 515–526.

Ray, D.K., P.C. West, M. Clark, J.S. Gerber, A.V. Prishchepov, and S. Chatterjee 2019. "Climate Change has Likely Already Affected Global Food Production." *PLoS ONE* **14**(5): e0217148.

Reséndiz-Infante, C., and G. Gauthier 2020. "Temporal Changes in Reproductive Success and Optimal Breeding Decisions in a Long-distance Migratory Bird." *Scientific Reports* **10**: 22067.

Reside, A.E., N. Butt, and V.M. Adams 2018. "Adapting Systematic Conservation Planning for Climate Change." *Biodiversity and Conservation* **27**(1): 1–29.

Rockel, B., Will, A., and Hense, A. (Eds.) 2008. "Special Issue: Regional Climate Modelling with COSMO-CLM (CCLM)." *Meteorologische Zeitschrift* **17**(4): 347–348.

Sander, A., M. Bathke, and K. Franz 2019. *Landesprogramm Ländlicher Raum (LPLR) des Landes Schleswig-Holstein 2014 bis 2020: Beiträge zur Evaluation des Schwerpunktbereichs 4A Biologische Vielfalt, 5-Länder-Evaluation*. entera Umweltplanung, Hannover.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi 2016. "What Would It Take to Achieve the Paris Temperature Targets?" *Geophysical Research Letters* **43**(13): 7133–7142.

Santangeli, A., A. Lehikoinen, A. Bock, P. Peltonen-Sainio, L. Jauhiainen, M. Girardello, and J. Valkama 2018. "Stronger Response of Farmland Birds than Farmers to Climate Change Leads to the Emergence of an Ecological Trap." *Biological Conservation* **217**: 166–172.

Schippers, P., and M.J. Kropff 2001. "Competition for Light and Nitrogen among Grassland Species: A Simulation Analysis." *Functional Ecology* **15**(2): 155–164.

Schöttker, O., and F. Wätzold 2022. "Climate Change and the Cost-effective Governance Mode for Biodiversity Conservation." *Environmental and Resource Economics* **82**: 409–436.

Schroeder, J., T. Piersma, N.M. Groen, J.C.E.W. Hooijmeijer, R. Kentie, P.M. Lourenço, H. Schekkerman, and C. Both 2012. "Reproductive Timing and Investment in Relation to Spring Warming and Advancing Agricultural Schedules." *Journal of Ornithology* **153**: 327–336.

Shah, P., M.L. Mallory, A.W. Ando, and G.R. Guntenspergen 2016. "Fine-resolution Conservation Planning with Limited Climate-change Information." *Conservation Biology* **31**(2): 278–289.

Sturm, A., M. Drechsler, K. Johst, M. Mewes, and F. Wätzold 2018. "DSS-Ecopay – A Decision Support Software for Designing Ecologically Effective and Cost-effective Agri-environment Schemes to Conserve Endangered Grassland Biodiversity." *Agricultural Systems* **161**: 113–116.

The European Commission. 2021. *EU Biodiversity Strategy for 2030: Bringing nature back into our lives*. Luxembourg: Publications Office of the European Union.

Thogmartin, W.E., L. López-Hoffman, J. Rohweder, J. Diffendorfer, R. Drum, D. Semmens, S. Black, I. Caldwell, D. Cotter, P. Drobney, L.L. Jackson, M. Gale, D. Helmers, S. Hilburger, E. Howard, K. Oberhauser, J. Pleasants, B. Semmens, O. Taylor, P. Ward, J.F. Weltzin, and R. Wiederholt 2017 "Restoring Monarch Butterfly Habitat in the Midwestern US: 'All Hands on Deck'." *Environmental Research Letters* **12**: 074005.

USDA (n.d.) *CRP Haying and Grazing: Emergency and Non-Emergency Use*. Factsheet. Available at https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/crp_haying_grazing_factsheet.pdf (accessed 21.06.2022).

USDA (2020) *Primary Nesting Season Dates and Duration*. Available at https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/primary_nesting_seasons_5_23_2022.pdf (accessed 21.06.2022).

US Fish and Wildlife Service (2010) *Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change*. Available at https://climatechange.lta.org/wp-content/uploads/cct/2015/02/CCStrategicPlan.pdf (accessed 23.05.2022).

Vos, C.C., P. Berry, P. Opdam, H. Baveco, B. Nijhof, J. O'Hanley, C. Bell, and H. Kuipers 2008. "Adapting Landscapes to Climate Change: Examples of Climate-Proof Ecosystem Networks and Priority Adaptation Zones." *Journal of Applied Ecology* **45**: 1722–1731.

Wätzold, F., M. Drechsler, K. Johst, M. Mewes, and A. Sturm 2016. A Novel, Spatiotemporally Explicit Ecological-Economic Modeling Procedure for the Design of Cost-effective Agri-Environment Schemes to Conserve Biodiversity. *American Journal of Agricultural Economics* **98**(2): 489–512.

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