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RESEARCH ARTICLE

REVISED Potential for positive biodiversity outcomes under diet-driven land use change in Great Britain [version 2; peer review: 1 approved, 1 approved with reservations]

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v2 **First published:** 06 May 2022, **7**:147
https://doi.org/10.12688/wellcomeopenres.17698.1
Latest published: 15 Feb 2024, **7**:147
https://doi.org/10.12688/wellcomeopenres.17698.2

Abstract

Background

A shift toward human diets that include more fruit and vegetables, and less meat is a potential pathway to improve public health and reduce food system-related greenhouse gas emissions. Associated changes in land use could include conversion of grazing land into horticulture, which makes more efficient use of land per unit of dietary energy and frees-up land for other uses.

Methods

Here we use Great Britain as a case study to estimate potential impacts on biodiversity from converting grazing land to a mixture of horticulture and natural land covers by fitting species distribution models for over 800 species, including pollinating insects and species of conservation priority.

Results

Open Peer Review

Approval Status ? ✔

	1	2
version 2 (revision) 15 Feb 2024		✔ view
version 1 06 May 2022	? view	? view

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Across several land use scenarios that consider the current ratio of domestic fruit and vegetable production to imports, our statistical models suggest a potential for gains to biodiversity, including a tendency for more species to gain habitable area than to lose habitable area. Moreover, the models suggest that climate change impacts on biodiversity could be mitigated to a degree by land use changes associated with dietary shifts.

Conclusions

Our analysis demonstrates that options exist for changing agricultural land uses in a way that can generate win-win-win outcomes for biodiversity, adaptation to climate change and public health.

Keywords
biodiversity, land use change, public health, conservation, diets, species distribution modeling

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Competing interests: No competing interests were disclosed.

Grant information: This work was supported by Wellcome [205200, https://doi.org/10.35802/205200] and the Natural Environment Research Council [NE/M019799/1]. This work is part of the Sustainable and Healthy Food Systems (SHEFS) programme supported by the Wellcome Trust's Our Planet, Our Health programme. R.G.P and H. F-G received additional funding from the Natural Environment Research Council (NERC ADVENT project).
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

How to cite this article: Ferguson-Gow H, Nicholas O, Outhwaite C *et al.* **Potential for positive biodiversity outcomes under diet-driven land use change in Great Britain [version 2; peer review: 1 approved, 1 approved with reservations]** Wellcome Open Research 2024, **7**:147 https://doi.org/10.12688/wellcomeopenres.17698.2

First published: 06 May 2022, **7**:147 https://doi.org/10.12688/wellcomeopenres.17698.1

REVISED **Amendments from Version 1**

We have now mapped the land conversions derived from alternative allocation strategies (new Figure 3), revealing contrasting spatial allocations that highlight the importance of spatial targeting in policies. We also restructured the Introduction and Methods sections to place all methodological details in Methods. We also added: a concise statement of our central aim (Introduction); additional text to describe and justify the dietary scenarios used (Introduction); more detail on the difference between current consumption levels of fruit and vegetables and the Eatwell target (Introduction); text noting the potential importance of different timescales in realizing the land use change scenarios (Discussion); clarification that our analysis of vegetables includes legumes (Discussion); and updated policy implications of the work (Discussion). Finally, we added details of funding for the Biological Records Centre, which provided data, to the Acknowledgements.

Any further responses from the reviewers can be found at the end of the article

Introduction

Replacement of animal-derived protein (meat and dairy products) with fruits and vegetables in human diets is associated with reduced mortality from cardiovascular disease and some forms of cancer (McEvoy *et al.*, 2012; Yip *et al.*, 2019) and offers multiple environmental benefits, including reductions in greenhouse gas emissions, land use footprints and terrestrial pollutants (Castiglione & Mazzocchi, 2019; Eustachio Colombo *et al.*, 2021; Scheelbeek *et al.*, 2020a; Willett *et al.*, 2019). Transformation of food systems is thus a key component of global (IPCC, 2019) and national (Climate Change Committee, 2019) efforts to mitigate climate change and support sustainable development (Willett *et al.*, 2019). Moreover, global studies have identified the potential of food system transformations to reverse negative trends in terrestrial biodiversity (Leclère *et al.*, 2020) such as the homogenization of biotic communities (Dornelas *et al.*, 2014), the loss of species richness (Newbold *et al.*, 2015) and declining population sizes (WWF, 2020). However, global-scale analyses are unable to address national-level policy debates that will be vital for realizing this potential. Here we use Great Britain as a case study to explore how biodiversity conservation, climate change mitigation and public health might be jointly enhanced within a national policy context.

In the UK, the Eatwell Guide provides national public-health based recommendations on the relative contribution of food groups to a healthy and balanced diet (Public Health England, 2016). The guide promotes a shift towards more plant-based diets and specifies that adults should eat at least five portions of fruit and vegetables per day, which falls short of the recommended 400g per day (Public Health England, 2020). Recent analysis has suggested that adherence to the Eatwell Guide is associated with reduced mortality as well as a reduction in diet-related greenhouse gas emissions (Castiglione & Mazzocchi, 2019; Scheelbeek *et al.*, 2020a). If the UK population were to adhere to the Eatwell Guidelines then there would need to be an increase in the supply of fruit and vegetables, which could be achieved through increased domestic horticultural production, increased imports of fruits and vegetables, or by a combination of the two. The UK currently imports about 84% of fruits and 56% of vegetables consumed (DEFRA, 2021a) and, although meeting increased demand by increasing imports would avoid impacts within the UK, there are several reasons to favour increased domestic production, including reducing reliance on supply from climate vulnerable countries, increasing UK food security and avoiding environmental impacts in other countries (Scheelbeek *et al.*, 2020b).

Compared to the production of plant-derived foods, the production of animal-derived foods requires more land per kcal dietary energy produced (Pimentel & Pimentel, 2003; Poore & Nemecek, 2018). For instance, 85% of the farmland globally that provides food for the UK is used to rear animals, yet animal-derived products provide only 32% of dietary energy consumed in the UK; by contrast, the 15% of farmland used to grow plants for human consumption provides 68% of dietary energy (de Ruiter *et al.*, 2017). Replacing meat with fruits and vegetables on a per-kcal basis could therefore reduce the land use footprint of the average diet. Currently 71% of the UK's land surface is used for agriculture (DEFRA, 2021b), so changes to patterns of land use (i.e., the relative amount used for animal- vs. plant-derived foods) could have a significant impact on the amount of land used for agriculture, and the amount available for other uses. To illustrate this, we consider the following two dietary scenarios for Great Britain (GB) in which meat is substituted with fruit and vegetables on a per-kcal basis to reach a threshold of 400g of fruit and vegetables consumed daily (consistent with the 5-a-day guideline). A number of previous studies have indicated that there would be benefits to both human health and greenhouse gas emissions from replacing meat with fruit and vegetables in UK diets, but most studies have not considered the origins of these foods or the potential co-benefits to biodiversity. The two scenarios were defined focusing on one important area of current environmental policy debate: whether consumption of fruit and vegetables produced in the United Kingdom should be prioritized over imported fruit and vegetable varieties to support national food security and resilience to climate change. The scenarios are detailed in Eustachio Colombo *et al.*, 2021 and are as follows: (1) in a domestic production only (DO) scenario, all additional demand for vegetables is met by expanding horticulture in GB (i.e., additional vegetables come from varieties that can be produced in GB); and (2) in a domestic/import (DI) scenario, current domestic production/import ratios are maintained (i.e., additional consumption is enabled by a combination of increased domestic production and increased imports). In the DO scenario, domestic horticultural production would be required to increase by 334% and meat production to decrease by 23%, and in the DI scenario domestic horticulture production would be required to increase by 123% and meat production to decrease by 30%.

When the DO and DI scenarios are converted into changes in land area (Methods), we find that in both scenarios the contraction in meat production accounts for a larger land footprint than the increase in horticulture production, meaning that under both scenarios land is made available for alternative uses. To explore the potential impacts of these shifts in land use on biodiversity, we examined cases whereby land taken out of meat production is first converted to horticultural production to cover the required increase in vegetables, and then the remaining land is converted to natural land covers. We did this for the DO and DI scenarios (Table 1) as well as for three example scenarios that are consistent with the maximum 30% reduction in grazing land in the DI scenario: 15% of grazing land replaced with horticulture and 15% with natural land; 10% of grazing land replaced with horticulture and 20% with natural land; and 5% of grazing land replaced with horticulture and 25% with natural land.

Table 1. Conversions of grazing land to horticulture and natural land cover for two scenarios of diet-driven land use change in Great Britain.

	Percent of grazing land converted	
Scenario	**To horticulture**	**To natural land cover**
Domestic only (DO)	5%	18%
Domestic/Import (DI)	3%	27%

Both scenarios reflect an increase in vegetable intake for the population of GB to 400g of fruit and vegetables per day with a corresponding calorie-for-calorie reduction in meat consumption. Grazing land includes the land cover types rough grazing, permanent grassland and temperate grassland; and natural land cover includes the land cover types natural woodland and natural grassland.

Our aim was to quantify the potential benefits to biodiversity that could come from diet-driven land use change. We did this by combining species occurrence records, climate change scenarios, and land use allocation strategies to model the potential distributions of 814 species in 4km^2 grid cells across GB.

Methods

Data sources

***Species occurrence records*.** Species were chosen based on their inclusion in two indicators used by the UK government to report on the status of UK biodiversity, including progress towards international conservation targets (JNCC, 2021): the priority species indicator (Indicator C4) and the pollinating insects indicator (Indicator D1c), bolstered by additional bee and hoverfly species (see underlying data Ferguson-Gow *et al.*, 2022). We obtained occurrence records underpinning these indicators, which are derived from various national recording schemes and societies (Table 2), from the UK Biological Records Centre. These data are used to generate the UK biodiversity indicators, ensuring consistency between our analyses and UK biodiversity indicators. The data were cleaned to ensure that the taxonomy was consistent and spurious records were discarded. Species observations were first collated from the various national recording schemes. These observations, or biological records, are presence-only data usually collected by volunteers as part of the recording scheme or society and consist of information on what

Table 2. Recording schemes and societies contributing data.

Aquatic Heteroptera Recording Scheme	Gelechiid Recording Scheme
Bees, Wasps and Ants Recording Society	Grasshoppers and Related Insects Recording Scheme
British Arachnological Society, Spider Recording Scheme	Ground Beetle Recording Scheme
British Bryological Society	Lacewings and Allies Recording Scheme
British Dragonfly Society	National Moth Recording Scheme
Dragonfly Recording Network	Riverfly Recording Scheme: Ephemeroptera
British Myriapod and Isopod Group; Centipede Recording Scheme	Riverfly Recording Scheme: Plecoptera
British Myriapod and Isopod Group; Millipede Recording Scheme	Riverfly Recording Scheme: Trichoptera
Chrysomelidae Recording Scheme	Soldier Beetles, Jewel Beetles and Glow-worms Recording Scheme
Conchological Society of Great Britain and Ireland	Soldierflies and Allies Recording Scheme
Dipterists Forum: Cranefly Recording Scheme	Terrestrial Heteroptera Recording Scheme - Plant Bugs and Allied Species
Dipterists Forum: Empididae, Hybotidae and Dolichopodidae Recording Scheme	Terrestrial Heteroptera Recording Scheme - Shield Bugs and Allied Species
Dipterists Forum: Fungus Gnat Recording Scheme	UK Ladybird Survey
Dipterists Forum: Hoverfly Recording Scheme	Weevil and Bark Beetle Recording Scheme

species was observed, where it was observed and when it was observed. Since these data are often collected opportunistically and do not follow a sampling protocol, the information associated with individual records can vary, particularly in terms of spatial and temporal resolution. As a result, the raw observations were standardized and only those with consistent spatial and temporal precision taken forward. Only those records where the date was known to the day and where the location of the record could be specified at the 1km x 1km precision were used. Only records from the year 1970 onwards were included since the number of records at the required spatial precision tends to be very low before this period. Only records from within the UK were retained (excluding data from the Channel Islands, the Republic of Ireland and the Isle of Man). Any records at a taxonomic level higher than species were removed. The remaining species lists were then checked by scheme organisers to ensure synonyms were accounted for and to aid in the determination of species aggregates where necessary (for example, if changes in taxonomy over the time period of interest had occurred). After completion of the checks, duplicate records were removed. More information on this process can be found in the 'Data Standardisation' section of Outhwaite *et al.* (2019). Due to data availability our species pool represents a subset of the C4 DEFRA indicator.

To account for the fact that the UK may experience novel climates in the future and to more accurately characterise the climatic envelope of our species pool we modelled the climatic envelope of each species across their range in Western Europe, rather than just in the UK. The study area we used was between -8.2 and 2.7 longitude and 50 and 60.1 latitude, excluding Ireland and Northern Ireland. We obtained European occurrence records for bumblebees from the STEP project (Potts *et al*., 2011; Rasmont *et al*., 2015) and records for the remaining species from GBIF by querying the database for the species binomial and all known synonyms (Derived dataset GBIF.org, 2022). The GBIF records were cleaned using the R package CoordinateCleaner (v2.0-2), which removes potentially spurious records (e.g. those clustered around museums or research stations; Zizka *et al*., 2019). We used default settings in CoordinateCleaner: maximum record age of 1980 and minimum precision of 2 x 2 km. Finally, we rarefied the data to ensure that each cell in our study area contained a maximum of one occurrence record per species. Eighteen species with no European records (either the data were unavailable, or the species does not occur on mainland Europe) were retained to maximise the size of our dataset. We considered a species with fewer than 40 records in Great Britain as having insufficient data and thus eliminated them from the analysis. This left us with 1070 species in our species pool (457 pollinating insects and 613 priority species).

We generated pseudoabsences for each species by randomly sampling points from cells that: a) did not contain an occurrence record for the species; and b) were not within one cell of a cell that contained an occurrence record for the species. To ensure that the pseudoabsences represented the study area fairly, our sampling was uniform across the study area and we sampled either 500 pseudoabsences or an equal number to the occurrence records, whichever was higher (Barbet-Massin *et al*., 2012).

Climate data. We used bioclimatic variables obtained from CHELSA (Karger *et al*., 2017) to predict habitat suitability across the study area for our chosen species. We used mean annual temperature, isothermality, mean annual precipitation and precipitation of the wettest month as our predictors. These variables are broad measures of temperature and precipitation and, given the taxonomic breadth of our dataset, we considered that they would be the most generically powerful to predict suitability for the widest range of species.

For future climate projections we obtained monthly predictions of maximum temperature, minimum temperature and precipitation from four global circulation models (MIROC-ESM-CHEM, NorES1-M, IPSL-CM5A-LR, GFDL-ESM2M, HadGEM2-ES) for every month in the time period 1970–2060 from the bias-corrected ISIMIP input dataset (Hempel *et al*., 2013; Warszawski *et al*., 2014). These data were then converted into annual bioclimatic variables for each of the years in the time period 1979–2060 using the R package dismo v1.3-5 (Hijmans *et al*., 2021). These data are at a much lower spatial resolution than the 2 x 2 km grid we were working to, so we used the scaling factor method to downscale the projections using the data from the years 1979–2013 to estimate a baseline (Fordham *et al*., 2011). We then calculated the mean bioclimatic variables for each decadal period for each GCM giving four projections per decade, and then generated a mean across all GCMs to give a single ensemble mean projection of bioclimatic variables for the 2050s.

Land use data. We used a UK land cover dataset that divides the UK into 2 x 2 km cells and describes the proportion of each cell that falls into each of 24 different land use classes, as described in Bateman *et al.* (2013; see extended data (Ferguson-Gow *et al*., 2022)). Because the proportions of land use classes in each cell add to 1, we used logistic regression models for occurrence with all land use proportions included, but no constant term.

We obtained data from Lovett *et al.* (2014) to characterise each cell in the study area as suitable or unsuitable for agriculture and prevented any changes to the land use in cells considered unsuitable. Approximately 42% of the 2 x 2 km cells in our study area were considered suitable for land use change.

Conversion of production changes to land area. DO scenario: Current grazing land (52,127 cells) is reduced by 23%, leaving 40,138 cells as grazing and 11,989 cells to redistribute. Horticulture (currently 600 cells) increases by 334% = 2,604 cells, which as a percent of the total current grazing cells = 2604/52127 = 5%, and the number of cells left for natural land cover = 11,989 - 2,604 = 9,385 cells (18% of grazing land).

DI scenario: Current grazing land (52,127 cells) is reduced by 30%, leaving 36,489 cells as grazing and 15,638 cells to redistribute. Horticulture (currently 600 cells) increases by 123% = 1,338 cells, which as a percent of the total grazing cells = 1338/52127 = 2.6%, and the number of cells left for natural land cover = 15,638 - 1,338 = 14,300 cells (27.4% of grazing land).

Species distribution models

We used a two-step modelling process to construct our SDMs: first we estimated the climatic envelope for each species across Western Europe and used this to project climate suitability in GB (Pearce-Higgins *et al.*, 2015; Pearson *et al.*, 2002); and second, we used Bayesian logistic regression to model species occurrence within climatically suitable areas of GB as a function of 24 land cover classes. We ran the SDMs under current climate and under a future mid-range climate scenario (RCP 6.0) to test whether land use changes could, in part, mitigate the impacts of climate change.

Modelling species climatic envelopes. The occurrence records and pseudo-absences were used to establish the climatic envelope of each species by constructing ensemble species distribution models using BIOCLIM, generalised linear models (GLM) and random forest algorithms as implemented in the R package dismo (Hijmans *et al.*, 2021). We selected these three algorithms due to their varying reliance on absence data, and ability to perform well across relatively small study areas and under a wide range of data conditions. Each model was evaluated using five-fold cross-validation; we calculated the area under the receiver-operator curve (AUC) for each round of validation, taking the mean AUC as a measure of model performance. Models with AUC < 0.6 were discarded. Any species that did not achieve AUC ≥ 0.6 for at least two of the fitted models was removed from the analysis. This resulted in the elimination of 256 species, and a final dataset of 814 species (Ferguson-Gow *et al.*, 2022). For each model we generated a presence/absence prediction by identifying the threshold that maximises the sum of specificity and sensitivity (Liu *et al.*, 2013). Finally, we produced an ensemble prediction of presence or absence across the study area by combining the three models using a majority consensus rule: if two-thirds of the models predicted presence in a cell then that cell is present in the ensemble. This is a simple approach that accounts for the fact that the output of different algorithms may not be directly comparable (Marmion *et al.*, 2009). This process was repeated for each combination of relative concentration pathway and decade to generate predictions of each species climatic envelope under potential future conditions.

Modelling species response to land use. Land use modelling was performed using the same GB occurrence records as we used for the climatic envelope modelling. Pseudoabsences were sampled from across GB from cells that were: (a) climatically suitable for the species, as predicted by our ensemble SDMs; (b) did not have an occurrence record in them; and (c) were not within one cell of a cell that contained an occurrence record. By doing this we are assuming that a cell that is climatically suitable but does not have an occurrence record is unsuitable due to the land cover configuration rather than the climatic conditions of the cell.

We pooled all presence and pseudoabsence records along with their associated values for the first seven principal components of the land cover data. The first seven PCs accounted for 95% of the variance in land cover. We then fitted a binomial mixed-effects model to a random 80% of these data, modelling presence/absence as a function of the land cover PCs, estimating a random slope and intercept for each species in the dataset. The remaining 20% of the data was set aside for model evaluation. From the resultant model we extracted the global parameter estimates and the species-specific parameter estimates and used these to estimate an AUC and threshold for each species, electing to use the threshold that maximises the sum of the sensitivity and specificity (Liu *et al.*, 2013). This process was repeated five times such that each datapoint was in the test dataset once (five-fold model evaluation) and for each species we took the mean AUC as a measure of the predictive power of the model for that species, and the mean threshold. As before, species that did not achieve an AUC of at least 0.6 were eliminated from the analysis.

We used Bayesian modelling for the presence, and pseudo-absence, of each remaining species expressed as a species-specific logistic function of proportion of land use in each class, with no constant term, resulting in 814 models. Experts specified prior distributions for the coefficients of each model declaring that the smallest absolute change in land use that could result in a shift from 50% to 75% (or equivalently 25%) chance of presence is one percent of the land use cell size. This prior was operationalised in the form of a product of 24 independent normal distributions centred at zero. We used two priors: one in which the standard deviation of the independent normals was 1, meaning that a priori for each land use class (measured in units of percentage) there was a 68% chance that the corresponding log odds was between -1 and 1; the other where the standard deviations were 1/6, meaning that a priori for all land use classes there was a 68% chance that the corresponding log odds were between -1 and 1.

These models were used to predict the probability of presence/absence in each cell for each species across the UK under scenarios of land use.

These models are naive to climate (other than the deliberate bias in the pseudo-absences) which means that when making predictions it is possible to predict a species to be present in cells that are outside of its climatic niche. In order to ensure that we are not making such predictions we apply the final step of using the species-specific climatic envelope as a mask to set all predicted values outside of the climatic envelope to zero after prediction. This same approach was used to make inferences of change under future climates by simply using the climatic envelope for a future climate scenario as a mask.

Modelling land use change

Since there are numerous ways that land use change could be allocated spatially across the landscape, we explored alternative allocation strategies to understand how sensitive our results were to the choice of land use allocation. All analyses excluded areas considered unsuitable for agricultural land use change, such as national parks, peatlands and steep slopes. We changed land use in three different ways. First, in each cell where land use could be modified we exchanged a proportion of its grazing land (permanent grassland, temporary grassland and rough grazing) to horticulture, and a further proportion of grazing land in equal amounts to the three natural covers (semi-natural grass, farm woodland and other woodland). The proportions were the same in all cells, and the result was an exchange of land use classes at the national level of the same proportions.

For the second and third strategies, we ordered cells by the expected improvement in average species occurrence per unit area of land use exchanged from grazing to horticulture, thus ordering cells by the benefit of exchanging grazing with horticulture in each cell. Then, for a given national proportion of exchange from grazing to horticulture we made this exchange in each cell, in order starting with the cell which we expected stood to benefit the most from such an exchange, until the appropriate national proportion was achieved ('Best' strategy). Also, for a given national proportion of exchange from grazing to natural covers, we worked with the same ordered list of cells but in reverse order, starting with exchange in the cell where transfer to horticulture was expected to be worst ('Worst' strategy).

Modelling benefit to species

We used the models for each species in two ways. One was to forecast under a land use scenario the total probability for that species summed over the modifiable cells. We interpreted this figure as an expected area. Because there was uncertainty in each model's coefficients, we carried forward that uncertainty in this calculation using linearisation. The other was to forecast, under a land use scenario, the chance of a 10% increase in the area of each species. Again, due to uncertainty in each model, we carried forward the uncertainty in the model in this calculation. We derived distributions of the number of species benefiting, and harmed, at the 10% level, again taking into account uncertainties in the models.

Results

We estimate that across all GB land area where agricultural land use could change, the average habitable area of 814 species is 28% and each 10% of grazing land transferred to horticulture is associated with 1 to 2% reduction in average habitable area; by comparison, each 10% of grazing land converted to natural land cover is associated with a 6% increase in average habitable area. Thus, on average conversion of grazing to horticulture results in a small loss of biodiversity, but this is outweighed by potential gains from converting the surplus grazing lands to natural cover (Figure 1). As a result, all land conversion scenarios considered demonstrate the potential for gains to biodiversity, as measured by increases in average habitable area and more species gaining habitable areas by >10% than species losing habitable area by >10% (Table 3). For each species losing >10% habitable area, we find that 6.3 (5.4–7.6) species will gain >10% habitable area under the DO scenario, and 9.8 (8.3–11.4) species will gain >10% under the DI scenario.

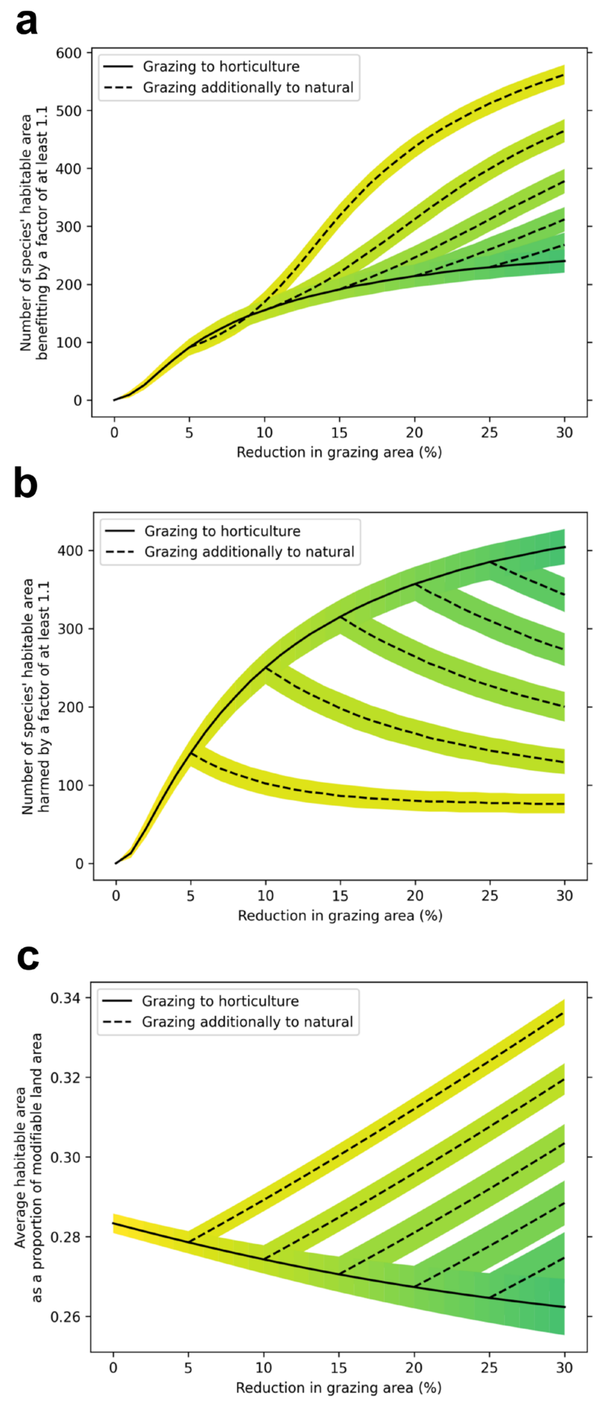

Figure 1. Projected species response to the replacement of grazing land with varying combinations of horticulture and natural land covers. **a**, The number of species that improve in habitable area by 10% or greater compared to their modelled habitable area under a no-change scenario. **b**, The number of species that decline in habitable area by 10% or greater compared to their modelled habitable area under a no-change scenario. **c**, The average habitable area as a percentage of modifiable land area. Solid black lines indicate a scenario where all grazing land removed from the landscape is replaced with horticulture. Dotted lines indicate scenarios where grazing land is replaced by horticulture until a certain percentage is reached (5, 10 and 15%) and then continues to be replaced by natural land covers.

Table 3. Projected biodiversity responses to land use and climate change scenarios.

Grazing land conversion scenario	Average habitable area	# species >10% habitable area increase	# species >10% habitable area decrease
No change	0.283 (0.281–0.286)	-	-
15% to horticulture, 15% to natural	0.303 (0.299–0.308)	378 (357–399)	200 (181–219)
10% to horticulture, 20% to natural	0.320 (0.316–0.323)	465 (445–485)	129 (114–146)
5% to horticulture, 25% to natural	0.336 (0.333–0.340)	562 (545–579)	76 (64–89)
5% to horticulture, 18% to natural (DO)	0.319 (0.316–0.322)	485 (467–504)	78 (65–91)
3% to horticulture, 27% to natural (DI)	0.343 (0.340–0.346)	599 (583–615)	63 (52–74)
No land conversion, with climate change	0.205 (0.203–0.206)	23 (16–30)	649 (641–658)
5% to horticulture, 18% to natural (DO), with climate change	0.233 (0.231–0.236)	125 (112–138)	485 (469–500)
3% to horticulture, 27% to natural (DI), with climate change	0.253 (0.250–0.255)	213 (199–228)	406 (392–420)

DO = Domestic only production scenario; DI = Domestic/import production scenario. Average habitable area is presented as a percent of modifiable cells. Climate change scenario is RCP 6.0 for 2050s. Values in parentheses are 95% credibility intervals.

Including climate change (scenario RCP 6.0) in our models resulted in projections of strongly negative impacts on biodiversity, with average habitable area dropping from 28% to 21% in the absence of land use conversions (Table 3). The number of species losing habitable area under climate change exceeds the number gaining habitable area: for each species gaining >10% habitable area, 4.1 (3.7–4.7) species will lose >10% under the DO scenario, and 2.0 (1.8–2.1) species will lose >10% under the DI scenario. Losses in habitable area due to climate change are larger than in any of our land use conversion scenarios, yet the models suggest that climate change impacts would be mitigated to some degree by the land use changes associated with a dietary shift from less meat to more vegetable consumption (e.g., average habitable area increases from 21% without land conversions to 23% under the DO scenario and 25% under the DI scenario; Table 3).

In terms of how land use change is allocated spatially across the landscape, we find that prioritizing converting the locations that stand to benefit most from the grazing to horticulture transition results in the best outcomes for biodiversity (Figure 2). Mapping the land conversions derived from alternative allocation strategies (Figure 3) shows remarkably different spatial patterns. Local allocation spreads the land use changes relatively evenly across the landscape, whereas Best and Worst strategies concentrate change in more restricted areas. Of particular note are the somewhat opposing allocations between the Best and Worst scenarios, with the Worst strategy largely allocating increased horticulture in England and the Best strategy allocating in Scotland and north Wales, and the Worst scenario largely allocating new natural land covers in Scotland and north Wales, while the Best scenario allocates mostly in England.

Discussion

Following national dietary recommendations has previously been shown to have broad benefits for public health (McEvoy *et al*., 2012; Scheelbeek *et al*., 2020a; Yip *et al*., 2019) and the environment (Jarmul *et al*., 2020; Payne *et al*., 2016; Poore & Nemecek, 2018). Our analyses demonstrate that land use changes associated with healthier diets could also have benefits for biodiversity in GB and potentially increase resilience to climate change. The biodiversity benefits that our models suggest occur largely because the dietary energy equivalent replacement of meat with vegetables has the potential to result in the use of less land for agricultural production, thereby freeing up land for alternative uses. Our analysis repurposed agricultural land for natural habitats and found potentially large benefits for biodiversity, including lessening the potentially negative impacts of climate change on species by providing greater opportunity for range expansions (Pearce-Higgins *et al*., 2015). This kind of 'rewilding' approach would of course

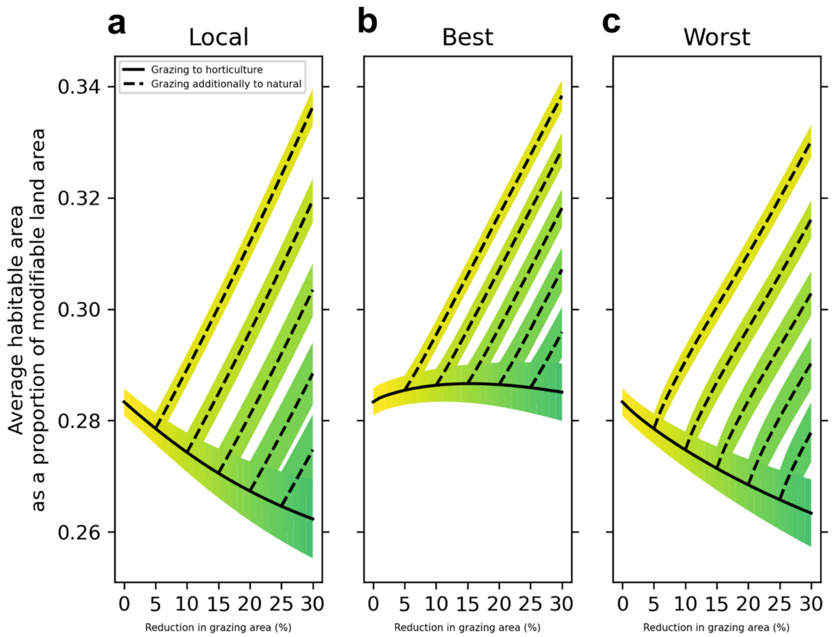

Figure 2. Change in average habitable area across all study species when grazing land is replaced with varying combinations of horticulture and natural land covers under three land use allocation strategies. a, Land use change is applied locally, proportionally to how much grazing land is present in each 4km^2 cell. **b** and **c**, We ordered cells according to our model's estimate, per unit area of transition from horticulture to grazing, of the benefit to the average habitable area of the 814 species. In **b** we allocated land use change to cells which had the best estimated benefit ('Best') and in **c** we allocated land use change to cells which had the worst estimated benefit ('Worst'), to provide contrasting land use allocation scenarios. Solid black lines indicate a scenario where all grazing land removed from the landscape is replaced with horticulture. Dotted lines indicate scenarios where grazing land is replaced by horticulture until a certain percentage is reached (5, 10 and 15%) and then continues to be replaced by natural land covers.

be a policy choice and alternate policy decisions could see the land put to other uses (e.g., green energy production or house building) that would result in different impacts on biodiversity. We note that rewilding and habitat restoration are challenging and can take time to deliver benefits (Perino *et al*., 2019; Pettorelli *et al*., 2018) but successful examples of rapid rehabilitation of nature exist (Tree, 2017; Tree, 2018). Our analyses did not specify a timeframe for realizing the different land use allocation scenarios, yet biodiversity responses are likely to be different depending on how rapidly land use change occurs. Exploring the temporal dynamics of how biodiversity will respond and the different policy decisions that could drive slow or fast change could be a fruitful avenue for further research.

We made some necessary assumptions about dietary substitution in our analysis. These assumptions were substantiated by data from previous modelling studies indicating that vegetables (including legumes) are a plausible substitute for meat (Springman *et al*., 2018; Tiffin *et al*., 2011), as well as very recent analyses of food consumption trends in the United Kingdom (Environmental Audit Committee, 2019). However, we cannot definitively determine that such substitutions would occur in practice and note the potential importance of novel plant-based foods in the future.

Although we assumed a 1:1 relationship between the percent change in production and the associated land use footprint, intensification of horticulture could further increase the area of agricultural land that could be taken out of production, providing further potential for expansion of natural habitats or alternative land uses. Likewise, intensification of livestock grazing could provide potential for expansion of natural habitats, though with detrimental impacts on animal welfare. The benefits of horticultural intensification would trade-off against potential negative impacts such as soil erosion, community homogenisation, and nitrogenous pollution (Tree, 2017) but sustainable intensification may be possible (Dicks *et al*., 2019; Finch *et al*., 2019; Gunton *et al*., 2016). We also note that our study only considered change in meat consumption, rather than all animal source foods including dairy. Considering dairy as well would be expected to further increase the amount of land available for conversion to natural habitats.

Our statistical biodiversity models provide first-pass estimates of species' responses to land use and climate change, but these methods have several limitations, including that they do not account for interactions between species or the potential for rapid adaptation, nor do they estimate the dispersal capacity of species (Pearson & Dawson, 2003). If an area is predicted to become more suitable for a species, it will still be necessary for the species to disperse through the landscape and colonize the new habitat, emphasising the need for connecting natural lands within resilient ecological networks (Isaac *et al*., 2018). This, combined with our finding that the

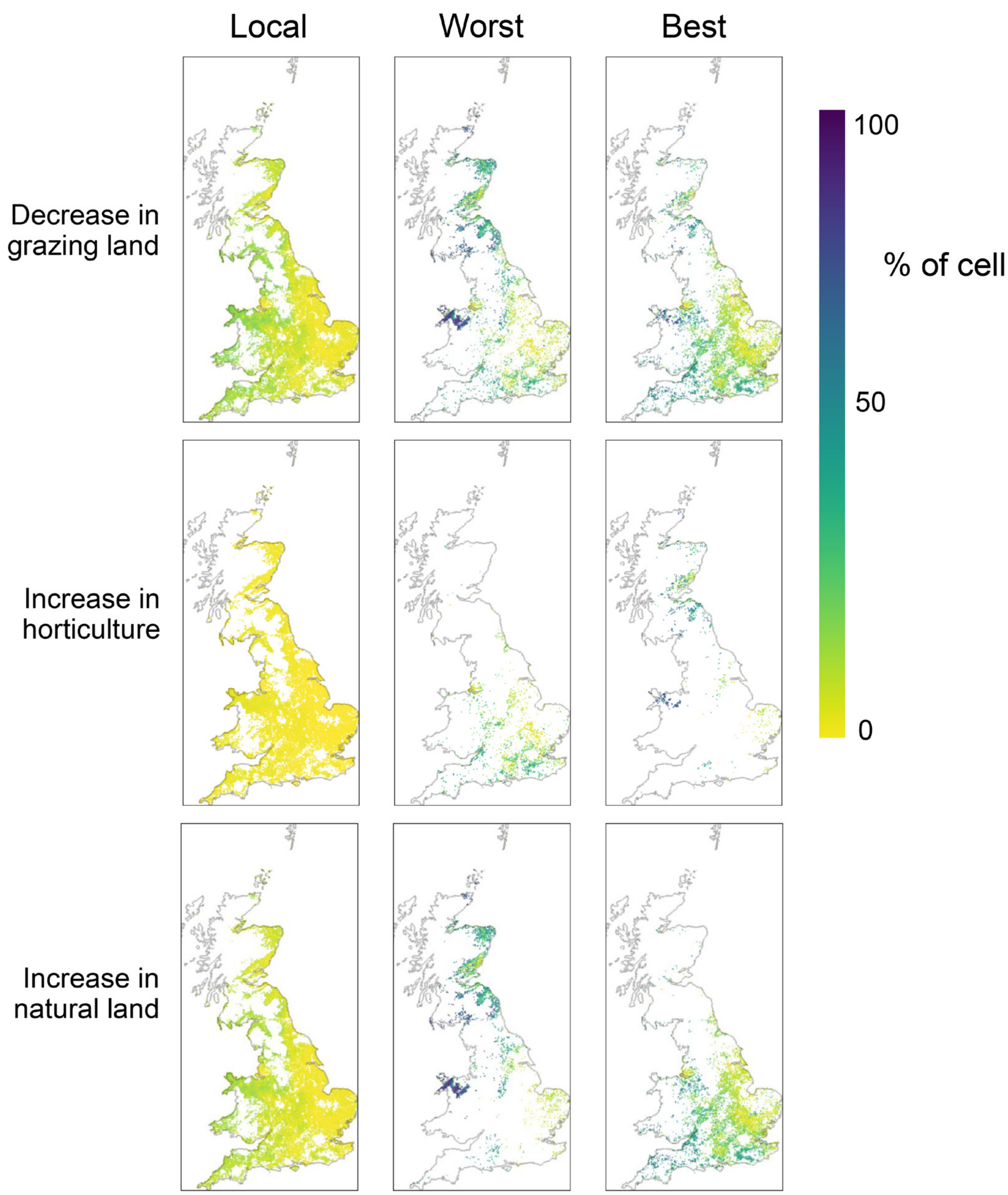

Figure 3. Mapped changes in grazing land, horticulture, and natural land under three land use allocation strategies. Land use change is applied locally, proportional to how much grazing land is present in a cell ('Local'); or land use change is applied first to cells that had the highest estimated benefit to biodiversity (Best) or first to cells that had the lowest estimated benefit for biodiversity (Worst). Results are expressed as a percentage of each 4km² cell.

spatial allocation strategy affects biodiversity responses, highlights the challenge and opportunity for policy makers to ensure that future conversion of agricultural land to natural habitats and rewilding are managed in such a way as to maximize the benefits to biodiversity.

Since our land conversion scenarios demonstrate larger benefits for biodiversity when the current ratio of domestic production to imports is maintained, versus when all additional demand is met by expanding horticulture in GB, it can be concluded that the best outcome for biodiversity in GB is to import more food and rely less on local production. However, our study did not look at the potential impact of diet changes beyond national borders. The current reliance of the UK on food imports compromises national food security, which is likely to be of particular importance as climate change alters patterns of trade, and also 'offshores' the environmental burden of UK diets to other countries, raising important questions about the equity of changes to national food systems (Scheelbeek *et al*., 2020b). For example, increased demand for tropical fruits and exotic vegetables has led to rising imports of products from climate vulnerable countries (Scheelbeek *et al*., 2020b). Further research is needed to better understand how global biodiversity impacts can be minimized in the context of international trade (Ortiz *et al*., 2021).

Our study has implications for land management policies. For instance, the 2021 independent review to inform a National Food Strategy for England suggested targets for a 30% increase in fruit and vegetable consumption and a 30% reduction in meat consumption (The National Food Strategy, 2021). While these targets have not yet been adopted by the government's official Food Strategy (Government food strategy 2022), our results indicate that they could be achieved at the same time as improving biodiversity and mitigating some of the expected impacts on biodiversity of climate change, if some grazing land was allocated to natural land covers. However, to make these shifts in land-use, environmental land management schemes, such as the Sustainable Farming Incentive, Local Nature Recovery scheme and Landscape Recovery scheme (DEFRA, 2022), will need to be designed to incentivise farmers accordingly. A particular challenge will be to achieve the best outcomes by developing policies that are spatially targeted (Bateman *et al*., 2013).

Conclusions

Our Our use of Great Britain as a case study helps improve understanding of how changing patterns of food consumption and associated land use within a state can be important in addressing environmental and health problems globally. By demonstrating the possibility of win-win-win outcomes, our analyses add to the growing evidence base that shows how reducing meat consumption in favour of increasingly plant-based diets can generate positive outcomes for public health, climate change mitigation, and biodiversity conservation.

Data availability

Underlying data

Zenodo: Underlying data for 'Potential for positive biodiversity outcomes under diet-driven land use change in Great Britain'. https://doi.org/10.5281/zenodo.5950710 (Ferguson-Gow *et al*., 2022).

This project contains the following underlying data:

- Data table 1. The 814 species that comprised the final dataset.
- Data table 2. The 24 land cover classes in the land cover dataset.

(ferguson-gow_*et_al*_2022_extended_data.xlsx)

Zenodo: Underlying data for 'Potential for positive biodiversity outcomes under diet-driven land use change in Great Britain'. https://doi.org/10.5281/zenodo.5939214 (Derived dataset GBIF.org, 2022).

This project contains the following underlying data:

- Data table 1. GBIF filtered species occurrence records.

(ferguson-gow_et_al_2022_gbif_data.xlsx)

Species occurrence records, derived from national recording schemes and societies (Table 2) were obtained from the UK Biological Records Centre. Anyone who wishes to gain access to these records can contact the Biological Records Centre (brc@ceh.ac.uk) and make a request. European occurrence records for bumblebees obtained from the STEP project are available from the corresponding authors (Potts *et al*., 2011; Rasmont *et al*., 2015). Bioclimatic variables obtained from CHELSA are available from: https://chelsa-climate.org/. The ISIMIP input data and data access instructions can be found here: https://www.isimip.org/gettingstarted/data-access/

Acknowledgements

Land use data were provided by N. Owen and B. Day (University of Exeter) via the ADVENT project. UK species occurrence records were provided by the Biological Records Centre based on data collated from the recording schemes and societies listed in Table 2. The work of the Biological Records Centre is supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCAPE programme delivering national capability. European species occurrence records were obtained from the Global Biodiversity Information Facility (GBIF) and occurrence records for bumblebees in Europe were provided by P. Rasmont and the STEP (Status and Trends of European Pollinators) project. We thank V. Groener, J. Williams, T. Newbold, D. Shen and members of the SHEFS programme team for helpful discussions.

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Open Peer Review

Current Peer Review Status: ? ✓

Version 2

Reviewer Report 22 February 2024

https://doi.org/10.21956/wellcomeopenres.22968.r74619

✓ **Mishel Unar-Munguía**
Instituto Nacional de Salud Pública, Morelos, Mexico

I have no further comments to the manuscript. The authors attended my comments and explained in detail the modeled scenarios. Thank you

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Population Nutrition, Health and nutrition economics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 17 July 2023

https://doi.org/10.21956/wellcomeopenres.19582.r58484

? **Mishel Unar-Munguía**
Instituto Nacional de Salud Pública, Morelos, Mexico

This is an innovative study that will add evidence of the benefits of land use change in favor of producing foods for a healthy and sustainable diet. Due to my area of expertise, my comments will focus more on diet and the selected scenarios.

It will be useful to provide information on current mean consumption in GB by food groups and also mention intake recommendations provided by the EATWELL guidelines.

With the information provided, I don't understand why the authors modeled a scenario where F&V should increase by 30% and meat should decrease by 30%. Also, in terms of kcal, a 30% reduction in meat intake would require a greater increase in the consumption of F&V since the energy density of these food groups is different.

From my point of view, there are no reasons explained to assume that reductions in meat should be substituted only with F&V. Why not include other plant-based food such as legumes and seeds?

The authors mention that in the domestic model, all F&V are produced in GB assuming that only F&V that could be locally grown are considered. What are these F&V? How do these differ from the F&V that are consumed from imports? Does the type of F&V produce affect the type and amount of biodiversity?

Regarding the grazing land conversion, the authors should explain more about the logic behind the scenarios. All these scenarios provide the same production/consumption of F&V and reduction of meat for the population. How, if the authors mention that intensity in the production was not modeled o increase?

Also, the time period modeled for land conversion is not clear. How many months/years should it take to convert grazing into horticulture land in this model?

Finally, some policy implications from the conclusions should be provided in terms of how to align policies in GB to incentivize not only agriculture changes but also to incentivize the consumption of F&V in the population

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Population Nutrition, Health and nutrition economics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 15 Dec 2023

Henry Ferguson-Gow

Response to review 2 Reviewer's comments are in black; our response is in red; text from the revised manuscript is in green. This is an innovative study that will add evidence of the benefits of land use change in favor of producing foods for a healthy and sustainable diet. Thank you.

Due to my area of expertise, my comments will focus more on diet and the selected scenarios. It will be useful to provide information on current mean consumption in GB by food groups and also mention intake recommendations provided by the EATWELL guidelines. We appreciate that this information will provide useful context for our study. We reference government statistics that give details about consumption levels and have now added to our manuscript a statement that summarises the average fruit and vegetable consumption, thus providing context as to how far away consumption is from the Eatwell target. The text now reads: "In the UK, the Eatwell Guide provides national public-health based recommendations on the relative contribution of food groups to a healthy and balanced diet (Public Health England, 2016). The guide promotes a shift towards more plant-based diets and specifies that adults should eat at least five portions of fruit and vegetables per day. However, recent levels of fruit and vegetable consumption are around 344g per day, which falls short of the recommended 400g per day (Public Health England, 2020)."

With the information provided, I don't understand why the authors modeled a scenario where F&V should increase by 30% and meat should decrease by 30%. Also, in terms of kcal, a 30% reduction in meat intake would require a greater increase in the consumption of F&V since the energy density of these food groups is different. We think the reviewer has misunderstood the scenarios we use. The reviewer is correct that reductions in meat intake will require greater increases in fruit and vegetables due to the different energy densities. This is, in fact, reflected in our scenarios. The following text describing the scenarios has been updated in Version 2 and we hope now provides clarity: "... we consider two narrative dietary scenarios for Great Britain (GB) in which current average meat consumption is substituted with fruit and vegetables on a per-kcal basis to reach a threshold of 400g of fruit and vegetables consumed daily (consistent with the 5-a-day guideline). A number of previous studies have indicated that there would be benefits to both human health and greenhouse gas emissions from replacing meat with fruit and vegetables in UK diets, but most studies have not considered the origins of these foods or the potential co-benefits to biodiversity. The two scenarios were defined focusing on one important area of current environmental policy debate: whether consumption of fruit and vegetables produced in the United Kingdom should be prioritized over imported fruit and vegetable varieties to support national food security and resilience to climate change. The scenarios are described in detail in Eustachio Colombo *et al*., 2021 and are as follows: (1) in a domestic production only (DO) scenario, all additional demand for vegetables is met by expanding horticulture in GB (i.e., additional vegetables come from varieties that can be produced in GB); and (2) in a domestic/import (DI) scenario, current domestic production/import ratios are maintained (i.e., additional consumption is enabled by a combination of increased domestic production and increased imports). In the DO scenario, domestic horticultural production would be required to increase by 334% and meat production to decrease by 23%, and in the DI scenario domestic horticulture production would be required to increase by 123% and meat production to decrease by 30%."

From my point of view, there are no reasons explained to assume that reductions in meat should be substituted only with F&V. Why not include other plant-based food such as legumes and seeds? Our analysis does, in fact, include legumes. We are sorry that wasn't clearer in Version 1. We have included the vast majority of calories that would come from vegetables (including legumes) and note that the percent of diet represented by seeds is likely to remain very small. We have added the following text to the Discussion to clarify this issue: "We made some necessary assumptions about dietary substitution in our analysis. These assumptions were substantiated by data from previous modeling studies indicating that vegetables (including legumes) are a plausible substitute for meat (Tiffin et al. 2011; Springman et al. 2018), as well as very recent analyses of food consumption trends in the United Kingdom (Environmental Audit Committee 2019). However, we cannot definitively determine that such substitutions would occur in practice and note the potential importance of novel plant-based foods in the future."

The authors mention that in the domestic model, all F&V are produced in GB assuming that only F&V that could be locally grown are considered. What are these F&V? How do these differ from the F&V that are consumed from imports? These are fruit and vegetables that are already produced in the UK and have been identified as having potential for expansion. We cite Eustachio Colombo et al., 2021 as providing details; specifically, Supplementary Table 7 in that paper lists all fruits and vegetables produced in the UK, and Supplementary Table 4 lists fruits and vegetables consumed from imports.

Does the type of F&V produce affect the type and amount of biodiversity? This is an interesting question but we are not able with the data available to work out the impact ofo particular fruits and vegetables on biodiversity (e.g., we cannot estimate the specific impact of cucumber, cauliflower, or asparagus on particular species). Instead, our study is able to estimate the overall impact on biodiversity of a shift away from meat productions toward horticultural production (see results in Table 3).

Regarding the grazing land conversion, the authors should explain more about the logic behind the scenarios. All these scenarios provide the same production/consumption of F&V and reduction of meat for the population. How, if the authors mention that intensity in the production was not modeled to increase? The land conversion scenarios that we developed assume that changes in production are achieved by expanding or contracting the land use footprint of that type of agriculture, rather than by changing the intensity. We explain this in the manuscript here: "To translate these changes in production into land use footprints, we assume that changes in production come from expanding or contracting the land use footprint of that type of agriculture, such that a 1% change in production corresponds to a 1% change in the footprint of the appropriate land use type. The increase in production could also be achieved through intensification on existing agricultural land, but we do not consider intensification here so our approach gives a conservative estimate of the land that could be freed to benefit biodiversity (see Discussion).” And also here: “Although we assumed a 1:1 relationship between the percent change in production and the associated land use footprint, intensification of horticulture could further increase the area of agricultural land that could be taken out of production, providing further potential for expansion of natural habitats or alternative land uses. Likewise, intensification of livestock grazing could provide potential for expansion of natural habitats, though with detrimental impacts on animal welfare. The benefits of horticultural intensification would trade-off against potential negative impacts such as soil erosion, community homogenisation, and nitrogenous pollution (Tree, 2017) but sustainable intensification may be possible (Dicks et al., 2019; Finch et al., 2019; Gunton et al., 2016).” We maintain that this approach is robust in providing a conservative estimate of the land that could be freed from dietary change (conservative in so far as the gains in land could be greater if intensification also occurred).

Also, the time period modeled for land conversion is not clear. How many months/years should it take to convert grazing into horticulture land in this model? We modelled biodiversity responses to land use change scenarios without specifying a time frame since assessing the factors that could affect this (e.g., policy options, economic drivers) is beyond the scope of our study. Stating a timeframe is unnecessary for our analyses, but the reviewer is correct that this is an aspect of the work that we haven’t explored and we therefore added the following to the Discussion: “Our analyses did not specify a timeframe for realizing the different land use allocation scenarios, yet biodiversity responses are likely to be different depending on how rapidly land use change occurs. Exploring the temporal dynamics of how biodiversity will respond and the different policy decisions that could drive slow or fast change could be a fruitful avenue for further research.”

Finally, some policy implications from the conclusions should be provided in terms of how to align policies in GB to incentivize not only agriculture changes but also to incentivize the consumption of F&V in the population We see the work as highly policy relevant and conclude the manuscript with the following text (updated from Version 1): “Our study has implications for land management policies. For instance, the 2021 independent review to inform a National Food Strategy for England suggested targets for a 30% increase in fruit and vegetable consumption and a 30% reduction in meat consumption (National food strategy for England, 2021). While these targets have not yet been adopted by the government’s official Food Strategy (Government food strategy 2022), our results indicate that they could be achieved at the same time as improving biodiversity and mitigating some of the expected impacts on biodiversity of climate change, if some grazing land was allocated to natural land covers. However, to make these shifts in land-use, environmental land management schemes, such as the Sustainable Farming Incentive, Local Nature Recovery scheme and Landscape Recovery scheme (DEFRA, 2022), will need to be designed to incentivise farmers accordingly. A particular challenge will be to achieve the best outcomes by developing policies that are spatially targeted (Bateman et al. 2013).” However, while our study aims to empirically show the potential benefits of agricultural changes and diet shifts, it is beyond the scope of this manuscript to draw further conclusions about the policies that should be implemented to incentivize change. This will require detailed analysis of the policy landscape and pros and cons of alternative strategies, which is work we hope our study will inspire.

Competing Interests: No competing interests were disclosed.

Reviewer Report 19 May 2023

https://doi.org/10.21956/wellcomeopenres.19582.r56822

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The article is very interesting and seems innovative and pertinent in the current context, so it deserves to be published with the appropriate changes.

From the structure point of view, the document should be improved. The introduction should focus on the problematic, the objectives and the state of the art, and the methodology referred to in the introduction should come later.

In relation to the content, there is a lack of clear definition of the objectives of the article as well as the relevance of the data that justifies the conclusions, namely the outcomes for "biodiversity, adaptation to climate change and public health"[1].

It lacks some theoretical reference about the scenarios[2] and the type of scenario should be framed (narrative, spatial-explicit...). I also think that there is a lack of contextualization about the evolution of diets and the type of food and consumption pattern (meat-based, seasonal, biological, local) that justifies the construction of the scenarios, as well as the contextualization of public policy (e.g. land use, health...).

Regarding land use, what would be the advantage of using a finer spatial resolution? It is not explicit if the authors used a temporal analysis, i.e. two years of land use? If yes, then why didn't they use those transitions in the model? It should be better justified. A figure showing the workflow developed would helpful.

As for the results and discussion. Since the results are not mapped it is difficult to ascertain what the impacts on the territory and on spatial policy. What kind of territories are most subject to change? The territories of urban sprawl and in the proximity of cities where more intensive agriculture is practiced, what changes would they bring? In terms of politics and public participation? Do farmers have an interest in changing? What about the role of consumers? Finally, what is the role of politics and what kind of policies should be favored? What is the relationship found between these results and public health?

References

1. Rounsevell M, Reay D: Land use and climate change in the UK. *Land Use Policy*. 2009; **26**: S160-S169 Publisher Full Text
2. Gomes E, Banos A, Abrantes P, Rocha J, et al.: Agricultural land fragmentation analysis in a peri-urban context: From the past into the future. *Ecological Indicators*. 2019; **97**: 380-388 Publisher Full

Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Land use systems, GIS and spatial analysis, Land use planning

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 15 Dec 2023

Henry Ferguson-Gow

Response to review 1 Reviewer's comments are in black; our response is in red; text from the revised manuscript is in green. The article is very interesting and seems innovative and pertinent in the current context, so it deserves to be published with the appropriate changes. Thank you.

From the structure point of view, the document should be improved. The introduction should focus on the problematic, the objectives and the state of the art, and the methodology referred to in the introduction should come later. We acknowledge that Version 1 had too much methodological detail in the Introduction. We have restructured the Introduction and Methods sections accordingly, moving descriptions of the conversion of production to land use footprint, the distribution modelling methods, and the spatial allocation approaches to Methods. We think that the division of information is now more appropriate and thank the referee for pointing this out.

In relation to the content, there is a lack of clear definition of the objectives of the article as well as the relevance of the data that justifies the conclusions, namely the outcomes for "biodiversity, adaptation to climate change and public health". As part of restructuring the

Introduction (above), we now end the Introduction with the following concise statement of our central aim and the datasets used to achieve this: “Our aim was to quantify the potential benefits to biodiversity that could come from diet-driven land use change. We did this by combining species occurrence records, climate change scenarios, and land use allocation strategies to model the potential distributions of 814 species in 4km^2 grid cells across GB.”

It lacks some theoretical reference about the scenarios and the type of scenario should be framed (narrative, spatial-explicit...). I also think that there is a lack of contextualization about the evolution of diets and the type of food and consumption pattern (meat-based, seasonal, biological, local) that justifies the construction of the scenarios, as well as the contextualization of public policy (e.g. land use, health...). Details about the dietary scenarios, including more context and much deeper justification of how and why they were constructed, are provided in our earlier paper (Eustachio Colombo et al., 2021). We had cited that paper in Version 1 but appreciate that some further details should be included in the revised paper. We have thus updated the key text describing the scenarios as follows: “... we consider two narrative dietary scenarios for Great Britain (GB) in which current average meat consumption is substituted with fruit and vegetables on a per-kcal basis to reach a threshold of 400g of fruit and vegetables consumed daily (consistent with the 5-a-day guideline). A number of previous studies have indicated that there would be benefits to both human health and greenhouse gas emissions from replacing meat with fruit and vegetables in UK diets, but most studies have not considered the origins of these foods or the potential co-benefits to biodiversity. The two scenarios were defined focusing on one important area of current environmental policy debate: whether consumption of fruit and vegetables produced in the United Kingdom should be prioritized over imported fruit and vegetable varieties to support national food security and resilience to climate change. The scenarios are described in detail in Eustachio Colombo *et al*., 2021 and are as follows: (1) in a domestic production only (DO) scenario, all additional demand for vegetables is met by expanding horticulture in GB (i.e., additional vegetables come from varieties that can be produced in GB); and (2) in a domestic/import (DI) scenario, current domestic production/import ratios are maintained (i.e., additional consumption is enabled by a combination of increased domestic production and increased imports). In the DO scenario, domestic horticultural production would be required to increase by 334% and meat production to decrease by 23%, and in the DI scenario domestic horticulture production would be required to increase by 123% and meat production to decrease by 30%.”

Regarding land use, what would be the advantage of using a finer spatial resolution? It is not explicit if the authors used a temporal analysis, i.e. two years of land use? If yes, then why didn't they use those transitions in the model? It should be better justified. A figure showing the workflow developed would helpful. The land use dataset we use was developed for the UK National Ecosystem Assessment and has been widely used since (see Bateman et al. 2013 *Science* 341(6141): 45-50). Use of a land use dataset with finer spatial resolution is unlikely to result in qualitatively different findings since the data set we use captures the proportions of different land use classes *within* each 2x2 km cell. We do not refer to temporal land use analysis because we did not use multiple years of land use data; instead, our analyses are agnostic as to the timeframes involved – aside from the climate change scenarios (which are for the 2050s), we modelled biodiversity responses to land use change scenarios without specifying a time frame. Stating a timeframe is unnecessary for our analyses, and would not be useful since different policies would realize the scenarios over different time frames; however, the reviewer is correct that this is an aspect of the work that we haven't explored and we therefore added the following to the Discussion: "Our analyses did not specify a timeframe for realizing the different land use allocation scenarios, yet biodiversity responses are likely to be different depending on how rapidly land use change occurs. Exploring the temporal dynamics of how biodiversity will respond and the different policy decisions that could drive slow or fast change could be a fruitful avenue for further research." We think that the revised Methods section now better describes the approach taken and therefore do not see a workflow figure as necessary.

As for the results and discussion. Since the results are not mapped it is difficult to ascertain what the impacts on the territory and on spatial policy. What kind of territories are most subject to change? The territories of urban sprawl and in the proximity of cities where more intensive agriculture is practiced, what changes would they bring? In terms of politics and public participation? Do farmers have an interest in changing? What about the role of consumers? Finally, what is the role of politics and what kind of policies should be favored? What is the relationship found between these results and public health? The challenge to map our outputs is insightful. We have now done this and present the results in a new figure (Figure 3). Specifically, we mapped the distribution of land use changes under the three allocation strategies (local, best, worst) for the Domestic Only scenario. This has revealed an important new result: that the spatial patterns for alternative land allocation strategies are very different, which raises an important challenge for policy-makers to design policies that are spatially targeted. We have now added the following text to the manuscript to reflect this new analysis: [Results:] "Mapping the land conversions derived from alternative allocation strategies (Figure 3) shows remarkably different spatial patterns. Local allocation spreads the land use changes relatively evenly across the landscape, whereas Best and Worst strategies concentrate change in more restricted areas. Of particular note are the somewhat opposing allocations between the Best and Worst scenarios, with the Worst strategy primarily allocating increased horticulture in England and the Best strategy allocating in Scotland and north Wales, and the Worst scenario primarily allocating new natural land covers in Scotland and north Wales, while the Best scenario allocates mostly in England." [Discussion:] "A particular challenge will be to achieve the best outcomes by developing policies that are spatially targeted (Bateman et al. 2013)." The reviewer additionally raises some important questions about policy implications and incentivising farmers. We conclude the paper with the following text (updated from Version 1): "Our study has implications for land management policies. For instance, the 2021 independent review to inform a National Food Strategy for England suggested targets for a 30% increase in fruit and vegetable consumption and a 30% reduction in meat consumption (National food strategy for England, 2021). While these targets have not yet been adopted by the government's official Food Strategy (Government food strategy 2022), our results indicate that they could be achieved at the same time as improving biodiversity and mitigating some of the expected impacts on biodiversity of climate change, if some grazing land was allocated to natural land covers. However, to make these shifts in land-use, environmental land management schemes, such as the Sustainable Farming Incentive, Local Nature Recovery scheme and Landscape Recovery scheme (DEFRA, 2022), will need to be designed to incentivise farmers accordingly. A particular challenge will be to achieve the best outcomes by developing policies that are spatially targeted (Bateman et al. 2013)." However, adding further discussion of the implications for policies and ways to incentivise farmers would require detailed policy analysis that is beyond the focus of this paper. Our central aim was to quantify the potential benefits to biodiversity that could come from diet-driven land use change, thus providing an empirical basis on which future policy work (addressing some of the questions raised by the reviewer) could build.

Competing Interests: No competing interests were disclosed.