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Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services

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Abstract

Bioenergy has been identified as a key contributor to future energy scenarios consistent with the Paris Agreement targets, and is relied upon in scenarios both with and without bioenergy with carbon capture and storage, owing to the multiple ways in which bioenergy can substitute fossil fuels. Understanding the environmental and societal impacts of land-use change (LUC) to bioenergy crops is important in determining where and how they could be deployed, and the resulting trade-offs and co-benefits. We use systematic review and meta-analysis to assess the existing literature on two poorly understood impacts of this LUC that are likely to have an important effect on public acceptability: cultural ecosystem services and biodiversity. We focus on the impact of LUC to non-food bioenergy crops on agricultural landscapes, where large-scale bioenergy planting may be required. Our meta-analysis finds strong benefits for biodiversity overall (up 75% ± 13%), with particular benefits for bird abundance (+81% ± 32%), bird species richness (+100% ± 31%), arthropod abundance (+52% ± 36%), microbial biomass (+77% ± 24%), and plant species richness (+25% ± 22%), when land moves out of either arable crops or grassland to bioenergy production. Conversions from arable land to energy trees led to particularly strong benefits, providing an insight into how future LUC to non-food bioenergy crops could support biodiversity. There were inadequate data to complete a meta-analysis on the effects of non-food bioenergy crops on cultural ecosystem services, and few generalizable conclusions from a systematic review of the literature, however, findings highlight the importance of landscape context and planting strategies in determining impact. Our findings demonstrate improved farm-scale biodiversity on agricultural land with non-food bioenergy crops, but also limited knowledge concerning public response to this LUC, which could prove crucial to the successful expansion of bioenergy to meet the Paris targets.

1. Introduction

Decarbonisation pathways that meet the Paris Agreement targets rely upon a vastly expanded role for bioenergy, both as a substitute to fossil fuel energy as well as to generate negative emissions using carbon capture and storage (BECCS) [1]. It has been estimated that to meet this future demand for bioenergy, large-scale deployment of non-food bioenergy crops, usually fast-growing trees and grasses, will require several hundred million hectares (Mha) of land, and much of this may come from conversion from food-based agricultural uses, including arable land currently used for food and feed crops and grassland for animal production [2, 3]. To meet a 2 °C temperature limit, land-use needs for BECCS alone stand at an estimated 380–700 Mha [4], equivalent to a land area 1–2 times the size of India [5].

According to the IPCC, this scale of land-use change (LUC) to non-food bioenergy crops is a potential threat to water and food security, sustainable development, and biodiversity, although co-benefits may also exist [6]. There is evidence that conversion from food-based agricultural land-use to non-food bioenergy crops can both enhance and degrade environmental processes and services [7–10], but much of the prior empirical research has focused on regulating services such as changes in soil carbon and greenhouse gas mitigation potential [11–13]. Other environmental and social impacts of non-food bioenergy crops are difficult to measure and are therefore poorly represented in land-use and environmental impact modelling tools [14, 15]. We explore two of these less-researched impacts of non-food bioenergy crops which could prove critical to ecosystem health and public acceptance of an expansion in bioenergy: biodiversity and cultural ecosystem services.

LUC represents the major driver of biodiversity loss in recent decades, with 47% of natural ecosystems in decline and around one million plant and animal species estimated to be at risk of extinction [16]. The expansion and intensification of agricultural land-use has simplified landscape structure, and extended the use of chemical inputs, undermining biodiversity and other ecosystem functions [17]. Understanding the impact of expanded non-food bioenergy cropping on plant and animal species is crucial and previous qualitative reviews have identified both positive and negative impacts of these crops on biodiversity, depending on the reference land-use and land management [7, 18–22]. The conversion of natural and semi-natural ecosystems to non-food bioenergy crops is likely to lead to negative impacts on biodiversity [20, 21, 23], as well as the loss of stored carbon [12, 13]. Whilst it is often assumed that an expansion of non-food bioenergy crops will largely occur on marginal unimproved semi-natural land rather than productive agricultural land, this assumption is likely too simplistic. Although sizeable opportunities for non-food bioenergy crop deployment may exist on land that does not conflict with either natural ecosystems or food production [24], in reality, these areas of land may not align with locations of bioenergy demand, adding to both financial and carbon costs of bioenergy [15]. This land may also be challenging for crop cultivation or prioritised for future food security instead of conversion to bioenergy cropping [25]. With farmland used for crop and livestock production currently covering one third of the land surface of the earth [16], we posit that if natural ecosystems are to be protected, freed-up agricultural land will be required for at least some of the increased future bioenergy cropping and this could support biodiversity and help reverse recent trends in species loss. Whilst some point to an inevitable conflict between land for food and for bioenergy [26], it is also possible that agricultural land will become available through increased precision agriculture and higher crop yields, alongside reductions in food losses and changes in dietary trends and associated declines in livestock and livestock feed requirements [27, 28].

LUC resulting from large-scale deployment of non-food bioenergy crops could also affect cultural ecosystem services. Cultural ecosystem services represent 'the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences', according to the 2005 Millennium Ecosystem Assessment [29]. These services are intangible, difficult to quantify, and often given little consideration [30]. Whilst research on these services in agricultural landscapes is limited, there has been progress in developing understanding of several of those more easily quantifiable: recreation utility of land has been ascribed high monetary value [14], and landscape aesthetic is an important factor in determining public attitudes towards onshore wind energy [31]. An expansion in land-use for non-food bioenergy crops will likely affect how people recreate and visually perceive the landscape, and there are concerns in some communities that these crops may have a negative impact on the visual landscape [32–34]. Our review therefore focussed on the impact of non-food bioenergy crops on the cultural ecosystem services of recreation and landscape aesthetic only.

Biodiversity underpins a number of important ecosystem functions and both biodiversity and cultural ecosystem service impacts of bioenergy crops could be critical to determining public acceptance of an expansion of non-food bioenergy crops in the landscape. The local impact of non-food bioenergy crops on biodiversity and cultural ecosystem services, as well as the communication of these impacts to the community, will represent key components of achieving a social license to operate (SLO) for bioenergy: the ongoing community support of a technology or activity [35]. Until now no meta-analysis has been applied to the conversion of agricultural land to non-food bioenergy crops in relation to biodiversity. In addition, no systematic review has been conducted on the impact of non-food bioenergy crops on the cultural ecosystem services derived from landscape aesthetics and recreation. As cultural ecosystem services are also affected by the biodiversity of an ecosystem [36], the impact that the non-food bioenergy crops have on biodiversity can also have indirect effects on cultural ecosystem services. Given these linkages, we address both gaps in the literature to consider future prospects for bioenergy expansion.

2. Materials and methods

2.1. Systematic review

Our systematic review and meta-analysis followed established protocols [37]. In the biodiversity meta-analysis, studies were assessed on the inclusion of the following: (a) primary data of the biodiversity

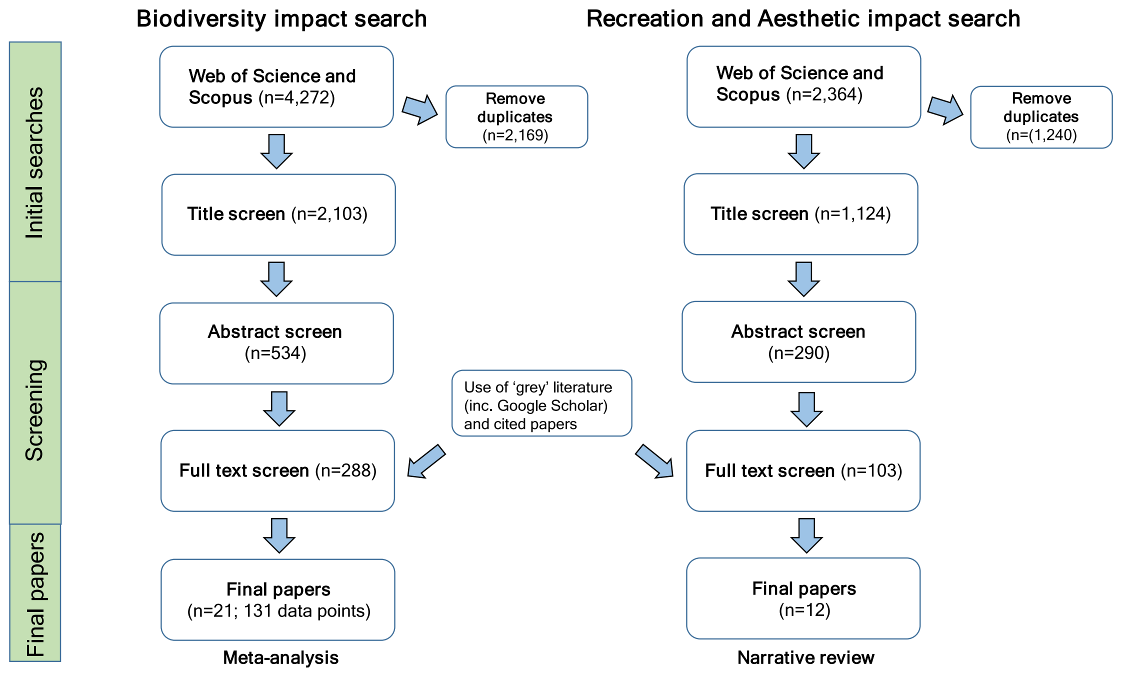

Figure 1. Flowchart of the review process of the two separate systematic searches of the biodiversity and recreation and aesthetic impacts of non-food bioenergy crops. Both searches were conducted in July 2020.

impact of food-based agricultural land-use (arable or managed grazing, defined to include permanent, semi-permanent, and rotation grassland) converted to a second generation non-food bioenergy crops; (b) assessment of a non-food bioenergy crop (*Miscanthus, Panicum viegatum* (switchgrass), prairie grass, short-rotation poplar and willow energy trees; (c) provision of response data for both the treatment (bioenergy crop) and control (food-based agricultural use), and; (d) data collected from a temperate region (excluding the polar circles and subtropic regions), excluding tropical crops from the scope of this current study. For the recreation and aesthetic systematic review we set the following inclusion criteria: (a) primary data of the recreational or aesthetic impact of LUC to non-food bioenergy crops; (b) assessment of a non-food bioenergy crop, as defined above; and (c) a location in a temperate region.

Search strings were first tested for their success in yielding papers identified as relevant to the study. The final search strings were used in the Web of Science and Scopus search engines (see table S1 (available online at stacks.iop.org/ERL/16/113005/mmedia)). Our systematic approach to the peer-review literature was augmented with targeted search of the 'grey' literature, using Google Scholar and visiting websites of relevant organisations. The results were downloaded into Excel spreadsheets where duplicates were removed, titles were screened for inclusion of a minimum of a word relating to bioenergy and a word relating to either biodiversity or recreation or aesthetic, before abstract reviews and then full paper reviews were completed, with the removal of papers failing to meet the inclusion criteria (see figure 1).

The biodiversity search of Web of Science and Scopus (conducted in July 2020) yielded 4272 results, in addition to grey literature searches, and 21 papers were found suitable for meta-analysis after removal of duplicates and the title, abstract, and full paper review process. The studies in these papers included data collected on a range of species and we split these based on their taxonomic coverage between four groups: birds, plants, arthropods, and below-soil organisms (including earthworms and microbial biomass). The studies typically compared several non-food bioenergy crops with at least one control land-use and measured the impact on more than one species group. For each combination of bioenergy crop, control land-use, and species group, an entry was made into the Excel data table. The 21 papers resulted in 131 observations of relevant data for the meta-analysis. We collected data on the sample size (n), standard error (SE), and mean (see SI). Where data were displayed in graphical form only, the software Data Thief [38] was used to extract numerical values. We contacted authors where relevant data were missing.

The cultural ecosystem service systematic review (conducted in July 2020) yielded 2364 results from Web of Science and Scopus, in addition to grey literature searches. This was reduced to 12 papers after removal of duplicates and the title, abstract, and full paper review process, with very few papers addressing recreation or aesthetic impact and many of those that did proving unsuitable because they did not study non-food bioenergy crops. Further quantitative analysis was not possible owing to a paucity of quantitative data and so a narrative review of the final papers was conducted in order to draw out relevant themes and conclusions.

2.2. Meta-analysis

Using the software OpenMEE [39] we ran the meta-analysis once for all species groups combined as well as additional runs for each species group and individual species where data were sufficient, for both abundance and species richness metrics. This led to nine separate effect sizes: all biodiversity (n = 104), bird abundance (n = 38), bird species richness (the number of distinct species observed; n = 19), *Alauda arvensis* (Eurasian skylark) abundance (n = 22), *Emberiza* genus (buntings) abundance (n = 5), plant species richness (n = 8), arthropod abundance (n = 17), earthworm abundance (n = 5), and microbial biomass (n = 17). In this study, the effect size represented the biodiversity change in the treatment (bioenergy) group compared to the reference agricultural land-use group. A log response ratio was calculated to represent the effect size: the natural log of the ratio of the mean value of the treatment (bioenergy) to the mean value of the control (arable or grassland). The log response was considered a more appropriate response metric than calculating the effect size using the standardised difference between group means (e.g. Hedges' g) because it does not use within-group variance in its calculation [40]. This is important since variance can vary notably between the studies owing to differences in study design such as geographic location, distribution, and taxonomic group [40]. The studies were weighted according to the inverse of individual study variance, and thus greater weight was given to larger studies with more precise effect estimates. A grand mean of all the log response effect sizes was calculated using a random-effects model, with the assumption that the true effect size varies between studies and that there is not one single true effect size (when a fixed-effects model is used). We acknowledge that some of variation between results was the result of study heterogeneity, including field size, time of year, and sampling method. However, reporting of these data was inconsistent across the studies we reviewed, and no analysis was conducted on these factors. We calculated between-study heterogeneity using the I^2 statistic (see SI for details). We also tested for publication bias - a bias towards the publication of positive results - using the funnel plot 'trim and fill' method [41], and assessed studies for evidence of pseudoreplication (see SI).

3. Results

3.1. Impacts on biodiversity

Overall, we found that LUC from cropland and grassland to non-food bioenergy cropping had positive effects on biodiversity, with species abundance increasing 73% ± 17% and species richness rising 80% ± 24%, when assessing all studies (figure 2(g)). Bird abundance was increased by 81% ± 32% (n = 38, figure 2(a)) in non-food bioenergy cropping landscapes compared to agricultural land-use of either arable or grassland. Bird species richness also increased, by 100% ± 31% (n = 19, figure 2(b)). Soil microbial biomass (n = 17) increased under LUC to non-food bioenergy cropping, by 77% ± 24% (figure 2(d)). Arthropod abundance (n = 17) was 52% ± 36% greater under non-food bioenergy crops (figure 2(c)), and plant species richness also increased compared to arable and grassland cropping: 25% ± 22% greater (n = 8; figure 2(e)). Whilst meta-analysis results for earthworms (figure 2(f)), *Alauda arvensis* (Eurasian skylarks; figure S9), and *Emberiza* (buntings; figure S10) were not significant, a number of the studies reviewed found positive impacts of LUC to non-food bioenergy crops for these species (37% ± 60%, p = 0.19; 18% ± 61%, p = 0.50; and 158% ± 271%, p = 0.16, respectively). Further analysis was completed to elucidate the biodiversity impact of specific LUCs: we found a greater observed increase in biodiversity under conversion to short-rotation energy trees compared to energy grasses, with particularly notable benefits for birds under conversions to energy trees (figures 3(a) and (b)), although conversions to energy grasses were not statistically significant for impact on bird populations (figure 3(a)). Bird biodiversity was also supported more under conversions from arable land compared to conversions from grassland (figures 3(a) and (b)).

3.2. Impacts on recreation and landscape aesthetic

Of the 2364 papers screened, just 12 addressed the specific question of the recreation or landscape aesthetic impact of non-food bioenergy crops. These studies provided data on public and landowner engagement, with three including qualitative research methods and eight including quantitative research methods (two of the four expert assessment studies used no research methods). A narrative summary of the findings of the 12 papers is provided in figure 4, with further details found in table S2. Three of the final 12 papers provided evidence that the public are less concerned with the visual impact of non-food bioenergy crops than the other aspects of bioenergy: power station infrastructure, air pollution, and road traffic [32, 34, 42]. However, all three of these studies identified some public concern regarding the visual impact of non-food bioenergy crops, with 'loss of

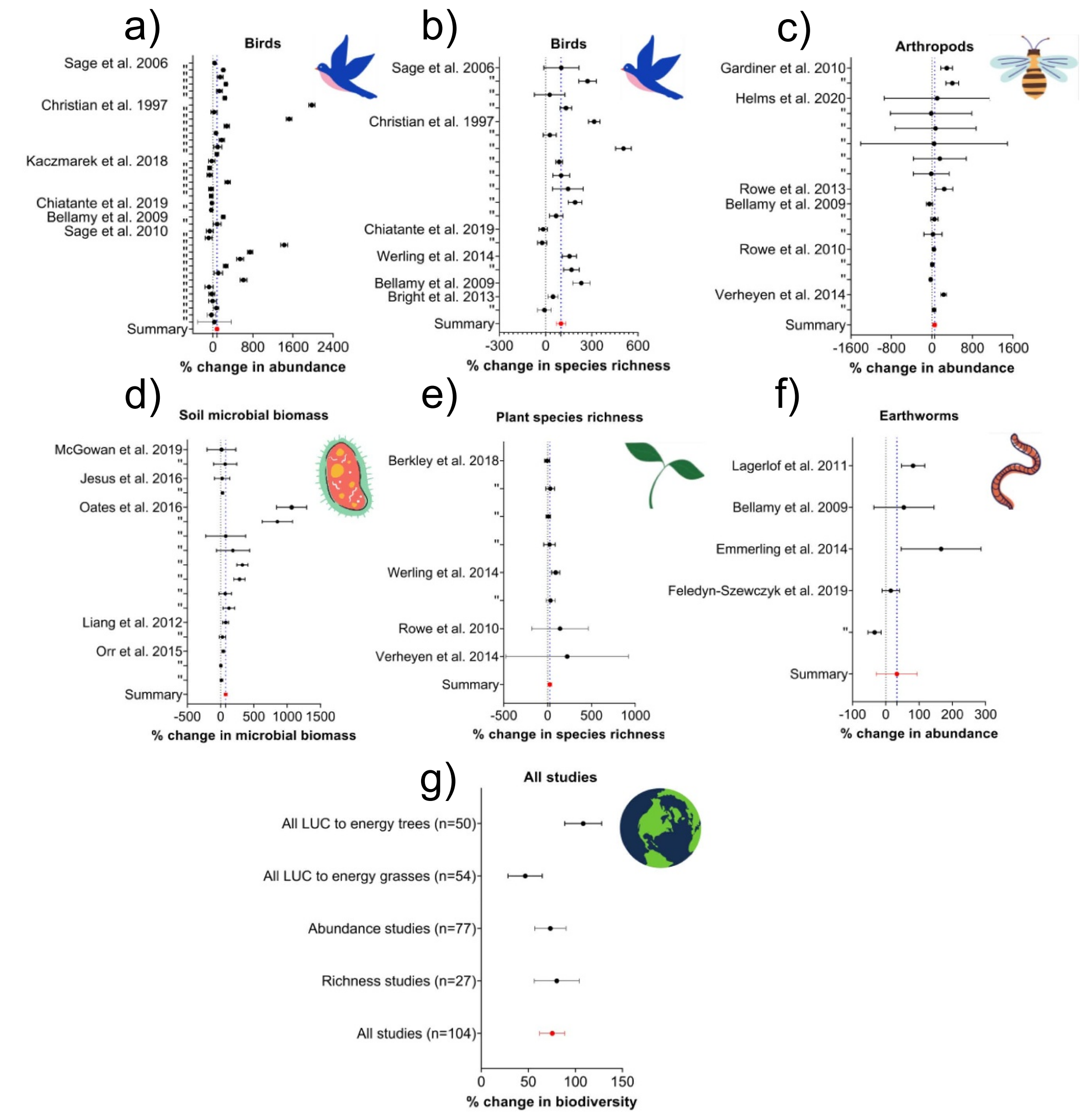

Figure 2. Meta-analysis of the impact on biodiversity taxonomic groups (bird abundance, bird species richness, arthropod abundance, microbial biomass, earthworm abundance, and plant species richness) of LUC from food-based agricultural land (arable and managed grassland) to non-food bioenergy crops (*Miscanthus*, switchgrass, prairie grass, short-rotation energy trees poplar and willow). Black circles represent mean values of individual study results, with 95% confidence intervals (CI), and red circles represent summary values, with 95% CI. Green dotted line shows overall summary value (weighted average) of each effect size. Bird abundance increases by an average 81% (±32%), bird species richness rose an average 100% (±31%), insect abundance increased an average 52% (±36%), soil microbial biomass increased an average 77% (±24%), and plant species richness increased 25% ± 22%. All results in figure 2 were statistically significant with the exception of results for earthworms (+37% ± 60%, $p = 0.19$).

view' and 'conspicuousness in the landscape' both frequently mentioned as a concern in a study employing focus groups [25].

Our systematic review found evidence that landscape context of non-food bioenergy crops shaped attitudes towards their aesthetic impact [32, 43–46], with several reports showing that public attitudes to these new crops are contingent on the features of the current landscape [43–46]. For example, Boll *et al* [43] showed that non-food bioenergy crops are supported in recreational areas with existing trees, but may be opposed in open landscapes. In contrast, Dockerty *et al* [32] found evidence that visual aesthetic benefits from bioenergy crop deployment can be realised where deployment increased landscape complexity or heterogeneity, which could occur in more open landscapes. Such contrasting findings from different regions highlight the complexity of drawing overarching conclusions around impacts that may be highly context specific. Further uncertainty arose with three of the public perception studies relying on questions without the use of visual aids [34, 42, 43], raising the question of whether the individuals involved understood the nature of this landscape change. In contrast, use of images [29, 45] and 3D 'real-time'

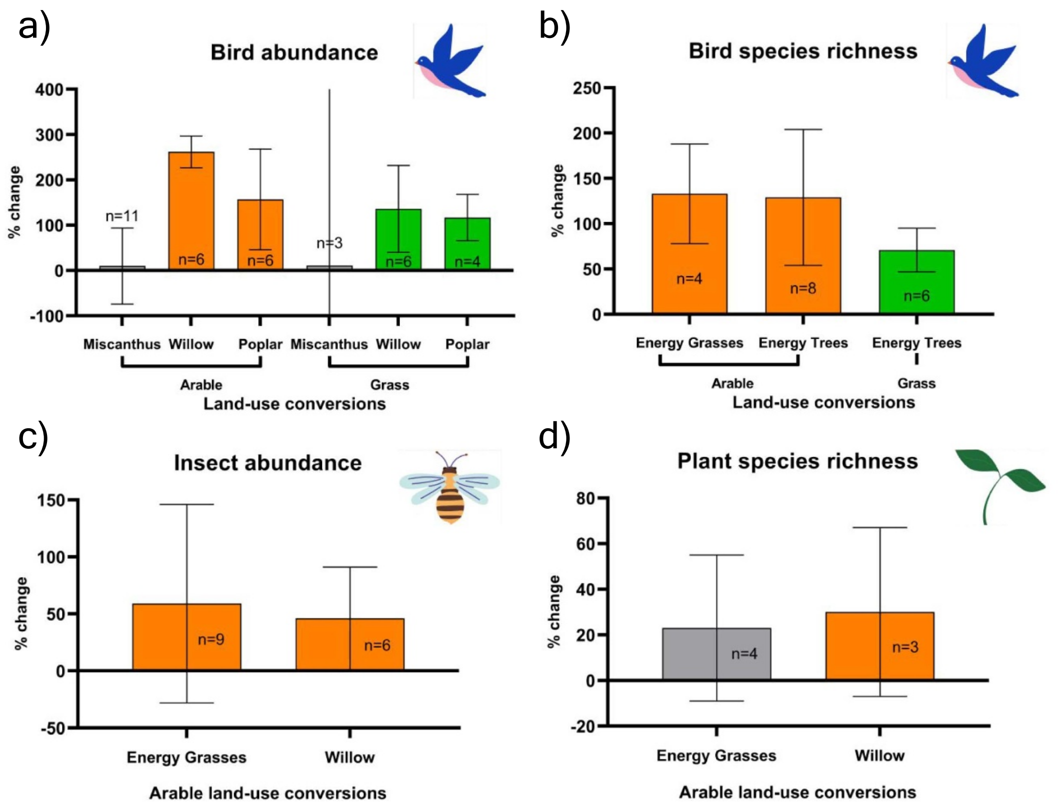

Figure 3. The biodiversity impact on species groups of specific land-use changes from agricultural land-use (arable or grassland) to non-food bioenergy crops of poplar, willow, and *Miscanthus*, or short-rotation energy trees (poplar or willow), or energy grasses (*Miscanthus*, switchgrass, and prairie grass). Bars represent mean values, with 95% CI shown. Sample size is shown by 'n'. Grey bar indicates non-significant result (shown by the Grass-*Miscanthus* ($p = 0.77$) and Arable-*Miscanthus* ($p = 0.92$) conversions for bird abundance and Arable-Energy Grasses ($p = 0.15$) conversion for plant species abundance). The error bar for the Arable-*Miscanthus* conversion impact on bird abundance does not fit on the axis. Separate axis scales are used for each pane.

landscape models [29] enabled interactive engagement for participants. Since public awareness and deployment of non-food bioenergy crops is relatively low [29], such tools may have an important role in the future expansion of non-food bioenergy crops.

One of the studies we reviewed presented evidence from a large-scale survey showing that farmers who valued landscape amenity were less likely to be willing to plant bioenergy crops [47]. This contrasted with further evidence, from individual interviews, that landowners supported bioenergy crops because of their visual aesthetic value and the provision of hunting cover for wildlife [48]. These conflicting and limited results preclude a firm conclusion on farmer attitudes on the landscape aesthetic impact of non-food bioenergy crops: the study location and context are both highly relevant to outcomes.

4. Discussion

Future bioenergy policy will need public support to be successful and this will be shaped by community engagement, how the bioenergy sector is expanded, and the impacts which follow [49, 50]. In this first meta-analysis on the impacts on biodiversity of agricultural LUC to non-food bioenergy cropping, we have shown that these crops can deliver significant biodiversity benefits, under the assumption that food-based agricultural land is freed up for their deployment. This represents a key finding given the important role of biodiversity in underpinning critical ecosystem functions and services. It suggests that non-food bioenergy cropping systems, that often utilize perennial rather than annual crops, have the potential to be more stable and resilient than annual arable cropping, although long-term field studies are required to confirm this effect. In contrast, with little evidence on the relationship between bioenergy crops and the cultural ecosystem services of recreation and aesthetic value, few conclusions could be drawn. This latter finding raises important questions about the public acceptability of large-scale non-food bioenergy crop planting. For example; following advice from its Committee on Climate Change, the UK government is considering a very large expansion in bioenergy, through deployment of BECCS, as a means of achieving the 2050 net-zero target [51], yet we do not understand how a rapid and large-scale expansion of non-food bioenergy crops would alter the landscape and whether it would be publically acceptable. Our work highlights a substantial knowledge gap in

Figure 4. Landscape impacts of non-food bioenergy crops are perceived differently by different stakeholders. Here we represent themes which emerged from the systematic review of recreation and aesthetic impact of planting non-food bioenergy crops: (a) reflects the lack of public understanding, engagement and information on the impact of non-food bioenergy crops in local landscapes; (b) summarises the values and motivations of farmers when considering whether to plant non-food bioenergy crops on the landscape; (c) local context is key to landscape decisions: who uses the landscape, how landscape features could change under non-food bioenergy crop planting, and the diverse attitudes of people recreating in that landscape context, and; (d) policymakers need to make decisions, such as meeting net-zero targets, whilst understanding the importance of other factors at the community level. This is challenging because these factors can be context specific and difficult to quantify.

understanding when the public is most supportive of opportunities for deployment of the technology and associated non-food bioenergy crops: closing this gap will be critical to increasing public acceptance.

4.1. Biodiversity

Conversion of food-based agricultural land to woody and perennial grass bioenergy crops results in improved biodiversity across species groups (figure 2), providing novel insight into an important driver for ecosystem services and adding to the existing literature of other ecosystem services supported by non-food bioenergy cropping, including soil organic carbon and flood mitigation [8, 9, 15, 52, 53]. Currently, agricultural landscapes are typically intensively managed and often dominated by the monocultures of several crops, driving negative impacts on biodiversity [17]. Our results reflect the positive biodiversity impact that non-food bioenergy crops can have in these landscapes, through less intense management, increased heterogeneity, and providing features more similar to natural ecosystems [20, 23, 54, 55]. The context of bioenergy planting will be important for determining biodiversity impacts locally, with management decisions, such as agrochemical inputs, weed control, tilling, vegetation structure, harvesting, and crop rotation all influencing outcomes [18–20]. Datasets on these additional factors were incomplete for the studies we reviewed, and therefore left out of the analysis. Crop location is also likely to shape biodiversity impacts. Research in the US midwest, where several intensively managed arable crops dominate the landscape, shows that a targeted expansion of perennial non-food bioenergy crops could support biodiversity as well as other ecosystem functions, as a result of reduced land management intensity and increased landscape-scale heterogeneity [56–58]. Our results featured a high concentration of studies in the USA and UK (16 of the total 21). Whilst these are two locations where non-food bioenergy crops could be expanded, the global applicability of our results should be treated with caution: other potentially important regions for non-food bioenergy crops such as eastern Europe and Asia are poorly represented in our analysis. Further studies in other countries and regions would help develop understanding of the non-food bioenergy crop impact on biodiversity globally.

The scale at which the deployment of non-food bioenergy crops can continue to deliver biodiversity benefits on agricultural land is a key question which requires further research. Most of our data were drawn from farm-scale studies, of fields typically sized under 10 ha, where non-food bioenergy crops added to landscape heterogeneity, known to be important to supporting biodiversity [54, 55]. However, if non-food bioenergy crops are concentrated in monocultures this could negatively affect biodiversity, as noted by several of the studies in our review, particularly in landscapes of high existing complexity. The IPCC states that high bioenergy land-use could have adverse biodiversity impacts but that supportive management at the appropriate scales could deliver biodiversity benefits [6]. Whether an expansion in non-food bioenergy cropping reduces or increases landscape heterogeneity will depend on existing landscape structure, farm-level decision-making, and the scale and concentration of future bioenergy demand, with farm-scale opportunities to increase landscape heterogeneity presumably reaching a saturation point, and large bioenergy power stations potentially requiring a concentrated nearby feedstock supply to reduce transportation costs.

Whilst the location, scale, and management of non-food bioenergy crop expansion will all be important, future improved crop yields and dietary shifts away from animal agriculture can also free up agricultural land for conversion to non-food bioenergy crops. Future land-use scenarios show that land demand for food could either fall or continue to rise in this century, depending on a number of factors including population and economic growth, dietary patterns and consumption of animal products, and crop and livestock yields [59, 60]. If land demand for the food-system continues to grow, and agricultural land is not freed up, then our results showing biodiversity benefits of land conversion to non-food bioenergy crops could be offset by indirect land use change (iLUC): bioenergy expansion (for example) in one location driving agricultural land expansion on natural ecosystems elsewhere. Our research here has only considered system-bound direct land use change to bioenergy cropping, rather than iLUC. These indirect or consequential impacts are beginning to be quantified in consequential life cycle analyses (C-LCA) [61] but are outside the scope of this study. If agricultural land is not used and bioenergy crops are instead grown on natural ecosystems, then biodiversity is also threatened: two recent reviews found evidence that conversion of natural ecosystem to non-food bioenergy crops was less harmful than conversion to first generation bioenergy crops, but that risks remained [20, 23].

An expansion in non-food bioenergy cropping could be of economic value to farmers if it leads to diversified farm businesses, facilitates higher crop yields through supporting pollinator species, and if policy incentivises delivery of ecosystem services [62]. However, our findings point to trade-offs for food production: whilst converting arable land to non-food bioenergy crops delivered greater biodiversity benefits than converting grassland, it also reflects a higher food production opportunity cost. Trade-offs may also exist at the level of bioenergy crop choice: conversions to energy trees (poplar and willow) delivered greater biodiversity benefits than conversions to energy grasses (*Miscanthus*, switchgrass, and prairie grass; figure 3), although these results were driven by the large number of bird studies reviewed and there could be other reasons, such as yield or water-use considerations, to favour energy grasses in specific contexts. A further limitation of our results concerns the bioenergy cropping impact on mammals, where a knowledge gap also noted by previous research [21, 63].

4.2. Recreation and aesthetic impact

It is difficult to reach firm conclusions regarding the recreation and landscape aesthetic impact of non-food bioenergy crop deployment at large-scale: the public have often not been exposed to these LUCs, and the disparate research methods across a limited number of relevant studies analysed rendered it difficult to reliably provide evidence for conclusions across multiple studies. Only two of the studies involved rigorous public engagement [32, 43] and they each employed different approaches concerning their questions and use of visual aids. Although both found some positive public attitudes regarding the recreation and landscape aesthetic impact of non-food bioenergy crops, these were context specific and found alongside concerns of the aesthetic impact of these crops.

Our findings reflected common challenges across cultural ecosystem service research: heterogenous research methods, results which are not translatable outside of the study context, and few studies seeking to replicate previous work across [30, 64]. Similar conclusions to ours have been reached on wind energy, a more mature renewable energy than second generation bioenergy crops: a meta-analysis of public responses to wind energy turbines found a wide range of research methods and only limited agreement on a set of basic visual impact variables, preventing definitive conclusions [65]. A further wind energy study found evidence of public sensitivity to wind turbine placement in landscapes of high aesthetic value, and high acceptance in unattractive landscapes [31], which could serve as a guide to inform bioenergy crop planting decisions. A review of previous studies to connect landscape features to aesthetic value concluded that no results have been achieved which could be translatable into policy [64]. One of these studies, a meta-analysis of photograph-based perception found that no variable of landscape character had a clear relationship with aesthetic value [66]. Landscape heterogeneity positively affects aesthetic value, according to one meta-analysis, echoing a finding of our review, although their result was based on just six studies [66], and ours only one [32]. Another review of studies on human perceptions of the landscape provided a summary of landscape features supporting landscape aesthetic value, supported by a low numbers of studies [67].

Similarly to the biodiversity study, the cultural ecosystem service papers reviewed did not address the impact of bioenergy monocultures. With limited evidence suggesting that landscape heterogeneity increases landscape aesthetic value, it could be expected that monocultures, which reduce heterogeneity, would undermine landscape aesthetic value [68]. Thus, bioenergy monocultures appear a threat to both biodiversity and cultural ecosystem services, through undermining landscape heterogeneity. Additionally, seven of the 12 studies in our systematic review were based in the UK, and all 12 were from either Europe or the USA, highlighting the lack of any evidence of these cultural ecosystem service impacts in agricultural landscapes across large parts of the world. One means of addressing this gap comes from using geo-referenced social media data as a proxy for recreation visits in landscape recreation research [69]. Results from this research suggests that recreation visits are not typically driven by landscape features, but instead by population density, accessibility, proximity to water, and mountainous terrain [70].

Policy guidelines on landscape aesthetic value typically draw on expert opinion, not primary research [64], and this is problematic because these guidelines may overlook visual impacts [71], as well as the potentially weak correlationbetween public views and expert views on landscape aesthetic value [67]. Moving forward, policy could be guided by two paths: firstly, avoiding deployment of non-food bioenergy crops in landscapes of high recreation or aesthetic value, where potential for negative impact appears greatest [72], and secondly; facilitating local-level decision making and information dissemination to ensure that community-level attitudes are voiced and non-food bioenergy crops are deployed in a way deemed acceptable by those who will be affected. Whilst our systematic review found evidence that farmers have motivations beyond financial considerations, with willingness to plant non-food bioenergy crops also influenced by land management goals such as pursuing amenity objectives [47], this may not be true in all contexts and a targeted expansion of non-food bioenergy crops which avoids monocultures and instead increases landscape complexity will require policymakers to incentivize and support farmers appropriately. This local-level engagement with the public and farmers could be crucial to achieving a SLO for an expansion in bioenergy. Community level engagement may also further our understanding of how non-food bioenergy crops impact the 'sense of place'—the nature of the connection that we hold to the landscape [47]. Although no evidence of this was found from our review, a sense of place has influenced attitudes towards other renewable energy technologies [73, 74].

5. Conclusions

Meeting net-zero targets through ambitious plans for accelerated non-food bioenergy crop planting requires decision-making which balances negative emissions generation alongside food production and protection of the natural environment. In this first meta-analysis to address the impacts of non-food bioenergy cropping on biodiversity in agricultural landscapes, we find significant biodiversity improvements at the farm-scale across a number of diverse taxa, where land is converted from either arable or managed grassland to tree and grass bioenergy crops. In contrast, the recreation and visual aesthetic impacts of non-food bioenergy cropping are harder to quantify with both positive and negative responses, depending on the specific context, reflecting a major knowledge gap. Taken together, these findings suggest that the proposed large-scale bioenergy expansion under energy scenarios consistent with net-zero policies and the Paris targets could be compatible with improved farm-scale biodiversity, if food-based agricultural land is freed up, but further research is required to determine the scalability of these results, alongside cultural ecosystem service impacts, if public acceptance and social legitimacy are to be achieved.

Data availability statement

We provide in the SI the data table of the final 12 studies used in our amenity review. Upon request of the authors an Excel table is available providing the full data-set used in the biodiversity meta-analysis.

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References

[1] Rogelj J *et al* 2018 Mitigation pathways compatible with 1.5°C in the context of sustainable development *IPCC Spec. Rep. Glob. Warm. 1.5°C* (available at: www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf)

[2] Beringer T, Lucht W and Schaphoff S 2011 Bioenergy production potential of global biomass plantations under environmental and agricultural constraints *GCB Bioenergy* **3** 299–312

[3] Slade R, Bauen A and Gross R 2014 Global bioenergy resources *Nat. Clim. Change* **4** 99–105

[4] Smith P *et al* 2016 Biophysical and economic limits to negative CO_2 emissions *Nat. Clim. Change* **6** 42–50

[5] Anderson K and Peters G 2016 The trouble with negative emissions *Science* **354** 182–3

[6] IPCC 2019 *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla, J Skea, E C Buendia, V Masson-Delmotte, H-O Pörtner and D C Ro

[7] Ferrarini A, Serra P, Almagro M, Trevisan M and Amaducci S 2017 Multiple ecosystem services provision and biomass logistics management in bioenergy buffers: a state-of-the-art review *Renew. Sustain. Energy Rev.* **73** 277–90

[8] Holland R A, Eigenbrod F, Muggeridge A, Brown G, Clarke D and Taylor G 2015 A synthesis of the ecosystem services impact of second generation bioenergy crop production *Renew. Sustain. Energy Rev.* **46** 30–40

[9] Milner S, Holland R A, Lovett A, Sunnenberg G, Hastings A, Smith P, Wang S and Taylor G 2016 Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB *GCB Bioenergy* **8** 317–33

[10] Robertson G P, Hamilton S K, Barham B L, Dale B E, Izaurralde R C, Jackson R D, Landis D A, Swinton S M, Thelen K D and Tiedje J M 2017 Cellulosic biofuel contributions to a sustainable energy future: choices and outcomes *Science* **356** eaal2324

[11] Harris Z M, Spake R and Taylor G 2015 Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions *Biomass Bioenergy* **82** 27–39

[12] Pogson M, Richards M, Dondini M, Jones E O, Hastings A and Smith P 2016 ELUM: a spatial modelling tool to predict soil greenhouse gas changes from land conversion to bioenergy in the UK *Environ. Model. Softw.* **84** 458–66

[13] Richards M *et al* 2017 High-resolution spatial modelling of greenhouse gas emissions from land-use change to energy crops in the United Kingdom *GCB Bioenergy* **9** 627–44

[14] Bateman I J *et al* 2013 Bringing ecosystem services into use in the United Kingdom *Science* **341** 45–50

[15] Donnison C *et al* 2020 Bioenergy with carbon capture and storage (BECCS): finding the win—wins for energy, negative emissions and ecosystem services—size matters pp 1–19

[16] IPBES 2019 Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services ed S Díaz, J Settele, E S Brondízio and H T Ngo

[17] Landis D A 2017 Designing agricultural landscapes for biodiversity-based ecosystem services *Basic Appl. Ecol.* **18** 1–12

[18] Immerzeel D J, Verweij P A, Van Der Hilst F and Faaij A P C 2014 Biodiversity impacts of bioenergy crop production: a state-of-the-art review *GCB Bioenergy* **6** 183–209

[19] Dauber J, Jones M B and Stout J C 2010 The impact of biomass crop cultivation on temperate biodiversity *GCB Bioenergy* **2** 289–309

[20] Núñez-Regueiro M M, Siddiqui S F and Fletcher R J Jr 2019 Effects of bioenergy on biodiversity arising from land-use change and crop type *Conserv. Biol.* **35** 1–11

[21] Riffell S, Verschuyl J, Miller D and Wigley T B 2011 A meta-analysis of bird and mammal response to short-rotation woody crops *GCB Bioenergy* **3** 313–21

[22] Meehan T D, Werling B P, Landis D A and Gratton C 2012 Pest-suppression potential of midwestern landscapes under contrasting bioenergy scenarios *PLoS One* **7** e41728

[23] Tudge S J, Purvis A and De Palma A 2021 The impacts of biofuel crops on local biodiversity: a global synthesis *Biodivers. Conserv.* **30** 2863–83

[24] Cronin J, Zabel F, Dessens O and Anandarajah G 2020 Land suitability for energy crops under scenarios of climate change and land-use *GCB Bioenergy* **12** 648–65

[25] Kang S *et al* 2013 Marginal lands: concept, assessment and management *J. Agric. Sci.* **5** 129–39

[26] Popp J, Lakner Z, Harangi-Rákos M and Fári M 2014 The effect of bioenergy expansion: food, energy, and environment *Renew. Sustain. Energy Rev.* **32** 559–78

[27] Committee on Climate Change 2020 The Sixth Carbon Budget: the UK's path to Net Zero (available at: www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf)

[28] Leclère D *et al* 2020 Bending the curve of terrestrial biodiversity needs an integrated strategy *Nature* **585** 551–6

[29] Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-Being Synthesis* (Washington, DC: Island Press)

[30] Milcu A I, Hanspach J, Abson D and Fischer J 2013 Cultural ecosystem services: a literature review and prospects for future research *Ecol. Soc.* **18** 44

[31] Molnarova K, Sklenicka P, Stiborek J, Svobodova K, Salek M and Brabec E 2012 Visual preferences for wind turbines:

location, numbers and respondent characteristics *Appl. Energy* **92** 269–78
[32] Dockerty T, Appleton K and Lovett A 2012 Public opinion on energy crops in the landscape : considerations for the expansion of renewable energy from biomass *J. Environ. Plan. Manage.* **55** 1134–58
[33] Upham P and Shackley S 2006 Stakeholder opinion of a proposed 21.5 MWe biomass gasifier in winkleigh, devon: implications for bioenergy planning and policy *J. Environ. Policy Plan.* **8** 45–66
[34] Upham P 2009 Applying environmental-behaviour concepts to renewable energy siting controversy: reflections on a longitudinal bioenergy case study *Energy Policy* **37** 4273–83
[35] Prno J 2013 An analysis of factors leading to the establishment of a social licence to operate in the mining industry *Resour. Policy* **38** 577–90
[36] Mace G M, Norris K and Fitter A H 2012 Biodiversity and ecosystem services: a multilayered relationship *Trends Ecol. Evol.* **27** 19–26
[37] Pullin A S and Stewart G B 2006 Guidelines for systematic review in conservation and environmental management *Conserv. Biol.* **20** 1647–56
[38] Tummers B 2006 *Data Thief III* (available at: http://datathief.org) (Accessed 12 November 2021)
[39] Wallace B C, Lajeunesse M J, Dietz G, Dahabreh I J, Trikalinos T A, Schmid C H and Gurevitch J 2017 OpenMEE: intuitive, open-source software for meta-analysis in ecology and evolutionary biology *Methods Ecol. Evol.* **8** 941–7
[40] Spake R *et al* 2020 Implications of scale dependence for cross-study syntheses of biodiversity differences *Ecol. Lett.* **24** 374–90
[41] Duval S and Tweedie R 2000 Trim and fill: a simple funnel-plot-based method *Biometrics* **56** 455–63
[42] Upham P and Shackley S 2007 Local public opinion of a proposed 21.5 MW(e) biomass gasifier in Devon: questionnaire survey results *Biomass Bioenergy* **31** 433–41
[43] Boll T, Von Haaren C and Albert C 2014 How do urban dwellers react to potential landscape changes in recreation areas? A case study with particular focus on the introduction of dendromass in the Hamburg Metropolitan Region *IForest* **7** 423–33
[44] Bell S 1994 Energy forest cultivation and the landscape *Biomass Bioenergy* **6** 53–61
[45] Bell S and McIntosh E 2001 *Short Rotation Coppice in the Landscape* Forestry Commission, Edinburgh
[46] Fawcett and Fawcett 2005 *Assessment of the Visual Impacts of SRC Plantations in Summaries of Biomass Projects in Energy from Biomass: summaries of projects carried out as part of the DTI's Technology Programme: New and Renewable Energy* ed Duffy G and Beale N Future Energy Solutions
[47] Eaton W M, Burnham M, Hinrichs C C, Selfa T and Yang S 2018 How do sociocultural factors shape rural landowner responses to the prospect of perennial bioenergy crops? *Landsc. Urban Plan.* **175** 195–204
[48] Hipple P C and Duffy M D 2002 Farmers' motivations for adoption of switchgrass *Trends in New Crops and New Uses* ed Janick J and Whipkey A (Alexandria, VA: ASHS Press) p 252–66
[49] Buck H J 2018 The politics of negative emissions technologies and decarbonization in rural communities *Glob. Sustain.* **1** 1–7
[50] Morrow D R *et al* 2020 Principles for thinking about carbon dioxide removal in just climate policy *One Earth* **3** 150–3
[51] HM Government 2020 *Powering our Net Zero Future* (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945893)
[52] Gasparatos A *et al* 2018 Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services *Biomass Bioenergy* **114** 157–73
[53] Englund O, Börjesson P, Berndes G, Scarlat N, Dallemand J-F, Grizzetti B, Dimitriou I, Mola-Yudego B and Fahl F 2020 Beneficial land use change: strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture *Glob. Environ. Change* **60** 101990
[54] Oliver T, Roy D B, Hill J K, Brereton T and Thomas C D 2010 Heterogeneous landscapes promote population stability *Ecol. Lett.* **13** 473–84
[55] Benton T G, Vickery J A and Wilson J D 2003 Farmland biodiversity: is habitat heterogeneity the key? *Trends Ecol. Evol.* **18** 182–8
[56] Schulte L A *et al* 2017 Correction: prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands *Proc. Natl Acad. Sci. USA* **114** 11247–52
[57] Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, Ong C K and Schulte L A 2014 Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services *Renew. Agric. Food Syst.* **29** 101–25
[58] Brandes E, McNunn G S, Schulte L A, Bonner I J, Muth D J, Babcock B A, Sharma B and Heaton E A 2016 Subfield profitability analysis reveals an economic case for cropland diversification *Environ. Res. Lett.* **11** 014009
[59] Popp A *et al* 2017 Land-use futures in the shared socio-economic pathways *Glob. Environ. Change* **42** 331–45
[60] Stehfest E *et al* 2019 Key determinants of global land-use projections *Nat. Commun.* **10** 1–10
[61] Sanchez S T, Woods J, Akhurst M, Brander M, O'Hare M, Dawson T P, Edwards R, Liska A J and Malpas R 2012 Accounting for indirect land-use change in the life cycle assessment of biofuel supply chains *J. R. Soc. Interface* **9** 1105–19
[62] Committee on Climate Change 2018 Biomass in a low-carbon economy (available at: www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf)
[63] Rowe R L, Street N R and Taylor G 2009 Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK *Renew. Sustain. Energy Rev.* **13** 271–90
[64] Bishop I D 2019 Evidence synthesis in landscape aesthetics: an honourable endeavour yet insufficient applicable knowledge *Socio-Ecological Pract. Res.* **1** 93–108
[65] Bishop I D 2011 What do we really know? A meta-analysis of studies into public responses to wind energy *Proc. World Renew. Energy Congr.—Sweden* (*Linköping, Sweden, 8–13 May*) **57** 4161–8
[66] Stamps A E 2004 Mystery, complexity, legibility and coherence: a meta-analysis *J. Environ. Psychol.* **24** 1–16
[67] Lothian A 2017 The Science of Scenery: How we see scenic beauty, what it is, why we love it, and how to measure and map it (San Bernardino, CA: CreateSpace)
[68] Manning P, Taylor G and Hanley M E 2015 Bioenergy, food production and biodiversity—an unlikely alliance? *GCB Bioenergy* **7** 570–6
[69] Wood S A, Guerry A D, Silver J M and Lacayo M 2013 Using social media to quantify nature-based tourism and recreation *Sci. Rep.* **3** 2976
[70] Van Zanten B T, Van Berkel D B, Meentemeyer R K, Smith J W, Tieskens K F and Verburg P H 2016 Continental-scale quantification of landscape values using social media data *Proc. Natl Acad. Sci. USA* **113** 12974–9
[71] Ode Å K and Fry G L A 2002 Visual aspects in urban woodland management *Urban For. Urban Green.* **1** 15–24
[72] Lovett A, Sünnenberg G and Dockerty T 2014 The availability of land for perennial energy crops in Great Britain *GCB Bioenergy* **6** 99–107
[73] Devine-Wright P 2011 Place attachment and public acceptance of renewable energy: a tidal energy case study *J. Environ. Psychol.* **31** 336–43
[74] Devine-Wright P 2009 Rethinking NIMBYism: the role of place attachment and place identity in explaining place-protective action *J. Community Appl. Soc. Psychol.* **19** 426–41