Investigating the impacts of climate change on ecosystem services in UK agro-ecosystems: An application of the DPSIR framework

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Abstract

Understanding how climate change will affect agro-ecosystems and the ecosystem services they provide is a significant global challenge. Investigating this topic requires a holistic approach that can capture the complexity of agro-ecosystems and assess impacts on the physical, biological, and socio-economic aspects of the system. The Drivers-Pressures-State-Impact-Response (DPSIR) framework is a problem structuring method commonly used in environmental policy and management to collate and synthesise multidisciplinary evidence. By reviewing relevant literature and policy documents, we created a DPSIR framework characterising the impacts of climate change on some key ecosystem services directly generated by farmland biodiversity, using UK agriculture as a case study. We focussed on three groups of service providers: pollinators, pest regulators and arbuscular mycorrhizal fungi. We used the standard DPSIR framework to establish broad-scale relationships, before developing two extensions to the initial DPSIR, which together formed a novel three-step approach. The second step allowed detailed exploration of the cause-effect relationships between different features of the agro-ecosystem, including cascading impacts on ecosystem services. This process highlighted knowledge gaps relating to the impacts of climate change on species interactions and cultural services. The third step provided a visual summary of the expected directional trends for the different features of UK agro-ecosystems, based upon current evidence. This demonstrated negative impacts on biodiversity, soil quality, crop yields and a wide variety of ecosystem services and goods, which can only be addressed effectively with targeted policies. The novel three-step DPSIR approach developed here would be useful for modelling other complex systems where management is impeded by knowledge gaps and the availability of accessible syntheses of current evidence.

Keywords

Arbuscular mycorrhizal fungi, Food security, Insect pest regulation, Multidisciplinary approach, Pollination, Problem structuring method

1 Introduction

Anthropogenic climate change is now widely recognised as an independent driver of environmental change, as past greenhouse gas emissions have committed the planet to a certain level of climate change, regardless of future human activities and emissions (IPBES, 2019; IPCC, 2013; UNEP, 2019). While land-use change and other drivers may appear more urgent threats to ecosystems in the short-term, climate change is expected to become a far more critical issue in the coming decades (IPBES, 2019). Climate change can negatively impact terrestrial ecosystems via increased surface temperatures, changed precipitation patterns, and increases in the severity and frequency of extreme weather events (IPCC, 2013). These changes will affect humans and society by directly reducing crop yields (Cai et al., 2015; Liu et al., 2016; Parry et al., 2004), which will impact global food security for a growing human population (IPCC, 2014). Climate change can also impact biodiversity, therefore affecting agricultural production indirectly by influencing organisms that interact with crops (IPBES, 2019). For example, climate change has already affected many species of insect that pollinate crops (IPBES, 2016; Parmesan and Yohe, 2003), and changing temperatures are predicted to increase the abundance of crop pests and pathogens (Bebber et al., 2014; Harrington et al., 2007). It is important to recognise the potential for climatic changes to affect all the non-crop biodiversity within agro-ecosystems because many organisms perform beneficial functions and services that can protect and enhance yields (MEA, 2005; UK NEA, 2011).

Agro-ecosystems are Social-Ecological Systems (SESs) where people manage the natural environment for the production of food and fibre (Gari et al., 2015; Lescourret et al., 2015). These ecosystems contain both domesticated and wild organisms, and so they also encompass the interactions within and between ecological and management processes. Agro-ecosystems provide a wide range of ecosystem services and goods that benefit humans, including crop production, pollination, and carbon sequestration (Lescourret et al., 2015; UK NEA, 2011). The relationships between these services and goods are complex and can involve synergies (positive interactions) or trade-offs (negative interactions), which makes management of agro-ecosystems extremely challenging (Lescourret et al., 2015; Power, 2010). Often these trade-offs occur between crop production and services provided by biodiversity (e.g., increasing insecticide use to increase yields could decrease natural pest regulation). Climate change therefore poses a potential double-threat to agro-ecosystem biodiversity, not only through the direct impact of changing environmental conditions, but also indirectly via management practices that aim to off-set crop yield decreases (IPBES, 2019). It is therefore imperative that we understand how climate change could affect both the social and ecological aspects of agro-ecosystems, and the cascading interactions between them, so that effective management can be designed and established. However, many of these social-ecological relationships are unclear, many of the climate change impacts on biodiversity are unclear, and few accessible syntheses of current knowledge are available, all of which could act as barriers to effective policy formation (IPBES, 2019; Lescourret et al., 2015; UK NEA, 2011; UNEP, 2019).

The Drivers-Pressures-State-Impact-Response (DPSIR) framework is a holistic tool that was developed to investigate environmental change and aid management in SESs (Gabrielsen and Bosch, 2003; Gari et al., 2015; Mosaffaie et al., 2021). The DPSIR framework is a problem structuring approach that allows the cause-effect relationships between anthropogenic activities and their environmental and socio-economic impacts to be explored and described in a sequential manner, while also accounting for feedback loops (Gari et al., 2015; Tscherning et al., 2012). DPSIR is well-suited for consideration of ecosystem services (Kelble et al., 2013; Omann et al., 2009; Rounsevell et al., 2010), agro-ecosystems (Bär et al., 2015; Holman et al., 2008; Rounsevell et al., 2010), and climate change (Bär et al., 2015; Holman et al., 2008; Omann et al., 2009; Rounsevell et al., 2010), because it can capture effects beyond the natural sciences. In the present case we can use the DPSIR framework as a tool to investigate the cascading impacts of climate change through agro-ecosystems. After first defining anthropogenic climatic changes as the problem(s) of interest (Drivers and Pressures), we can then investigate and characterise the established consequences of this problem on the different ecological features of the system (State), before exploring the known after-effects for the socio-economic features of the system (Impact) and the feedback mechanisms that aim to tackle these effects (Response). When used this way, the DPSIR categories provide us a with a structure that can help us to discover, define, and understand the sequences of cause-effect relationships between the different ecological and societal aspects of agro-ecosystems that are experiencing anthropogenic climate change (Gari et al., 2015). This application could also highlight missing links between the different elements within these causal chains, which represent gaps in the wider knowledge, while also presenting an accessible synthesis of that current knowledge that may be useful for decision-makers (Tscherning et al., 2012).

Here we present a novel application of the DPSIR framework investigating the impacts of climate change on the ecosystem services provided by biodiversity in arable agro-ecosystems, created using an evidence-based literature review methodology. Our case study focussed on arable farming in the UK, where there is a large body of relevant research from which we can draw, and where significant uncertainties relating to agro-ecosystem functioning and climate change have been demonstrated (UK NEA, 2011). Furthermore, the findings from this case may also be relevant more broadly across Northern Europe, given the common EU environmental policies (Common Agricultural Policy, Water Framework Directive, Habitats Directive etc.), and similar climate, biodiversity, and farming systems. Our objectives are fourfold: (1) to explore the suitability of the DPSIR framework as a tool to characterise the causal relationships between climate change, agro-ecosystem biodiversity, and the delivery of associated ecosystem services; (2) to use the DPSIR to determine key knowledge gaps (missing links in the causal chains) that require further investigation;

(3) to use the literature collated in the DPSIR to generate a visual summary of the likely impacts of predicted climatic changes on the different features of UK agro-ecosystems; and (4) to form the basis of an approach that can be developed for other countries and SESs.

2 Methods

2.1 Ecosystem services

Our DPSIR framework incorporates evidence from multiple fields and perspectives, therefore it is important that all ecosystem service classifications employed within the evidence-base can be integrated into the structure of the framework, without omissions or double-counting. The classification system developed for the Millennium Ecosystem Assessment (MEA) (MEA, 2005) is one of the earliest, but it is still commonly used in natural science literature, particularly in the context of areas relevant to our study, including soil research (Adhikari and Hartemink, 2016) and biodiversity conservation (Manhães et al., 2018). To this end, we adopted a hybrid system included in the UK NEA (Figure S1 in supplementary material), which recognises both the functional categories of the MEA (IPBES, 2016; La Notte et al., 2017; UK NEA, 2011) and the goods-focussed categories popular in socio-economic research (Elliott et al., 2017; La Notte et al., 2017). Supporting services underpin all others by providing physical structure, ecological niches, and captured/converted energy; regulating services moderate/maintain other environmental features that benefit society; provisioning services directly result in goods/benefits; and cultural services are the non-material benefits that people receive from experiencing nature, including recreation, inspiration, and health and well-being (MEA, 2005). We also consider ecosystem services to be links between an ecosystem and potential goods/benefits that require some form of 'complementary capital' to be realised (Elliott et al., 2017; La Notte et al., 2017).

We focussed on the ecosystem services provided by three of the most important groups of organisms in arable agro-ecosystems: (i) Pollinators – 35% of global crop production volume, and 87 of the most important global food crops, are dependent on animal pollinators (IPBES, 2016; Klein et al., 2007); (ii) Pest regulators – these organisms play a pivotal role in supressing pest populations, which results in improved crop yields and could reduce the need for insecticide use (Cardinale et al., 2003; Östman et al., 2003; Whelan et al., 2008); and (iii) Arbuscular mycorrhizal fungi (AMF) – symbiotic fungi that colonise the roots of around 80% of all plant species, contributing to soil stability, nutrient uptake, stress tolerance, pathogen resistance, and crop nutrition (Gianinazzi et al., 2010; Gosling et al., 2006; Smith and Read, 2008). We investigated the impacts of climate change on the regulating services directly delivered by these organisms, and also considered the downstream impact on crop production and cultural services.

2.2 DPSIR framework

We began by clearly defining the DPSIR categories for our application (following the recommendations in Gari et al. (2015)):

- **Drivers** are anthropogenic causes of system change, and so include climate change caused by anthropogenic greenhouse-gas emissions. Climate change is now widely accepted as an independent driver of environmental change, as past emissions ensure we are committed to further climatic changes regardless of future human activity (IPBES, 2019, 2016; IPCC, 2013; UNEP, 2019). Placing climate change in the first category also ensures it is considered as the starting point in our causal chains, which keeps the investigation focussed on our objectives: understanding the consequences of climate change, rather than the causes.
- **Pressures** are the mechanisms of change imposed upon the system by the Drivers. Defining climate change as a Driver allows the specific changes in temperature, precipitation, and extreme weather to be explored separately, which more accurately reflects the relevant scientific studies that typically only investigate one of these Pressures (Hegland et al., 2009; Liu et al., 2016).
- **State changes** include the biotic and abiotic changes in the natural environment that result from at least one of the Pressures and, as such, include relevant ecosystem services that constitute aspects of the physical, chemical, and biological environment.
- **Impacts** are changes in human welfare that follow-on from the State changes, which includes all the relevant ecosystem services and goods/benefits that constitute human and social aspects of the system.
- **Responses** represent relevant policy and management strategies that feedback within the system to influence the Drivers, Pressures, State changes and Impacts. These include both adaptation and mitigation measures and operate at a variety of spatial scales.

To examine large-scale problems with a DPSIR framework requires reliable information on many different environmental and social variables. Management applications often source quantitative data from existing monitoring systems, before filling the inevitable data gaps with qualitative data from expert/stakeholder consultation (Holman et al., 2008; Mosaffaie et al., 2021).

We overcame potential data-sourcing difficulties by populating our DPSIR with evidence gathered from non-systematic literature reviews, a common approach in research applications (Omann et al., 2009). Academic literature searches were conducted in 2019 using Web of Science (http://wok.mimas.ac.uk/) and Google Scholar (https://scholar.google.co.uk/) with search terms based on Drivers or Pressures (e.g. “climate change/warming”) in combination with environmental or socio-economic features of the system (e.g. “pollinator” or “food security”). See Table S1 for a summary of search terms. Non-academic literature (policy documents and governmental/intergovernmental research reports) was researched using the UK Government publication repository (https://www.gov.uk/government/publications) and the standard Google search engine (https://www.google.co.uk/). Where the literature was expansive (such as publications relating to crop yields), we included only those references most pertinent to our study system.

Once collected, this evidence-base was used to construct our DPSIR. Components were added to the framework where the literature identified them as being relevant to our research question. Components were arranged in the different categories in causal sequences according to literature that identified and defined these causal relationships. As such, any ecosystem services or abiotic and biotic features depicted in the completed DPSIR are included because there is evidence indicating a connection to one (or more) of our focal organism groups and climate change. Components in the Response category reflect the relevant legislation and policies in place at the time of conducting this research in 2019. Our literature-based approach to construction prevents us from proposing new policies or practices within Responses, they are instead considered in the discussion (section 4.3).

2.3 Three-step process

We were able to meet our first research objective by constructing a standard DPSIR framework that investigated environmental and societal repercussions of climate change in UK agro-ecosystems at a broad scale. However, addressing the second and third objectives required additional methods. Consequently, our results are presented in three stages:

1. A standard DPSIR framework that establishes the causal relationships between climate change, UK agro-ecosystem biodiversity, and ecosystem services and goods (objective 1);
2. A detailed and focussed iteration of the initial DPSIR that elaborates on the key relationships relating to the three focal organism groups (pollinators, pest regulators, and AMF), to more

clearly and completely show the cause-effect pathways and any knowledge gaps (objective 2);

3. A visual summary of the expected directional trends (including uncertainty) for each of the Pressures, State Changes and Impacts of the initial DPSIR, based upon current evidence (objective 3).

Steps 2 and 3 of this method involve making judgments with respect to the strength of the literature supporting the causal links and directional trends. Based on Hooper et al. (2017), each link is evaluated in terms of the volume and relevance of supporting evidence, and the degree of agreement between studies (Table 1).

Evidence Strength	**Evidence description**	**Step 2 Symbol** (Figs 2-4)	**Step 3 Symbol** (Fig 5)
Strong evidence	Many relevant papers documenting a direct link AND Consistent evidence on the nature/strength of the link		
Unclear/ limited evidence	1 or 2 relevant papers documenting a direct link OR Contradictory evidence on the nature/strength of the link OR Many papers documenting a direct link in a different system		
Very limited/ theoretical evidence	No relevant papers documenting a direct link BUT 1 or 2 papers documenting a direct link in a different system OR 1 or 2 papers documenting a theoretical link		

Table 1 Evidence strength categories and their corresponding symbols used to carry out steps 2 and 3 of the DPSIR analysis.

3 Results

The literature searches highlighted over 80 key papers, reports, and policy documents for inclusion within the DPSIR framework. References are denoted in figures using a number (see Table S2 for full list) and are pared down to include only the most recent relevant summary literature.

3.1 Step 1: DPSIR for UK agro-ecosystems

Our broad-scale DPSIR characterising the causal links between climate change and ecosystem services in UK agro-ecosystems can be seen in Figure 1. While most of the State changes found in the literature are regulating services, and most of the Impacts are cultural, there is crossover and both contain some provisioning, regulating, and cultural services. Most of the Responses currently in place in the UK take a reactive rather than proactive approach with respect to climate change, in that they feedback to directly address negative State changes rather than the Pressures or Driver (Figure 1).

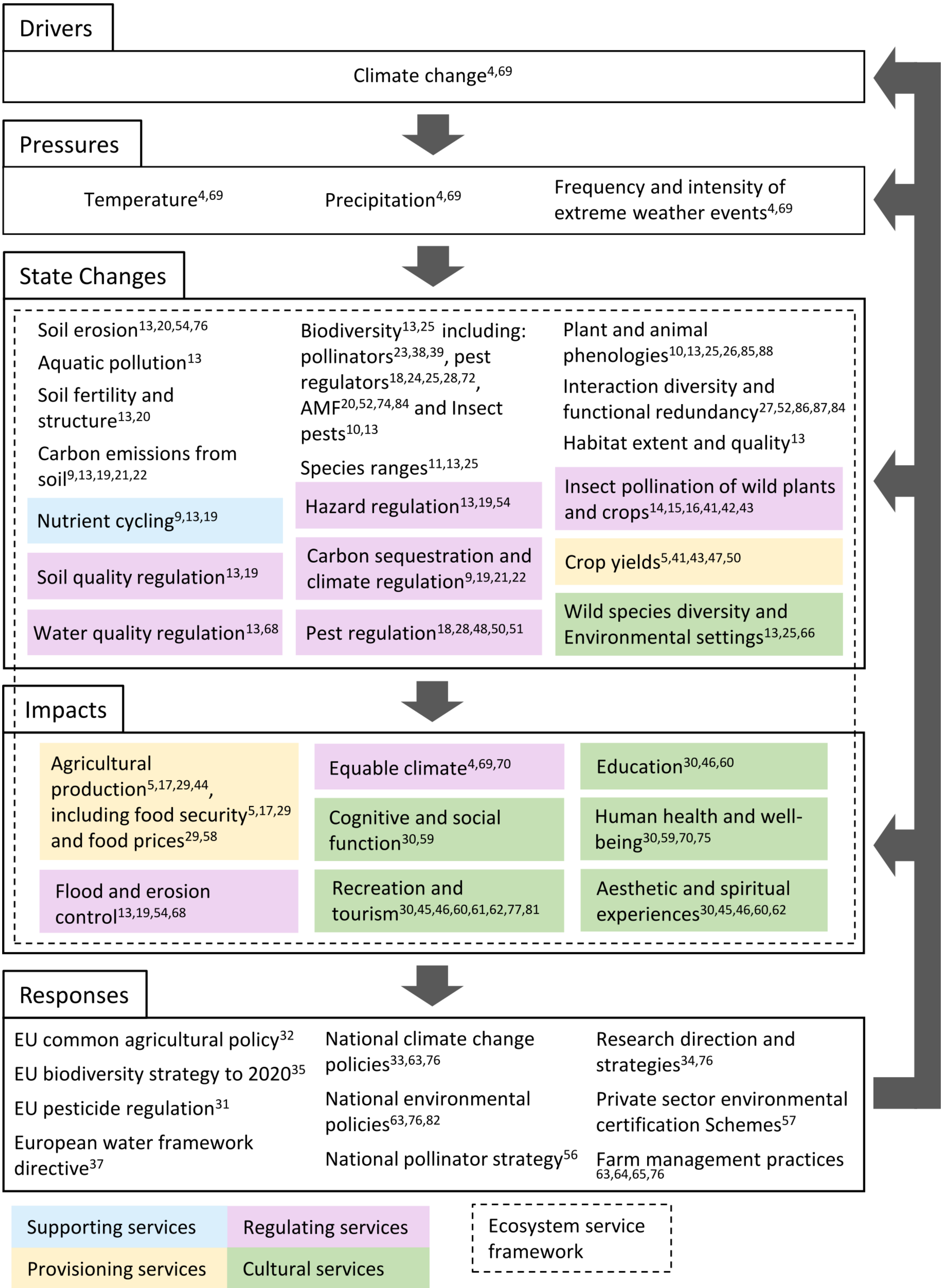

Figure 1 DPSIR framework created for UK arable agro-ecosystems. Superscript numbers represent references, see Table S2.

3.2 Step 2: Pathways and knowledge gaps

We highlighted the services provided by our focal organism groups of pollinators (Figure 2), pest regulators (Figure 3) and AMF (Figure 4), as well as key knowledge gaps within the literature, these are described below under separate subheadings for each group. Each focal group is presented in a separate figure to retain clarity, but we also present the combined results within a single framework (Figure S2). Focussing on these three groups simplified the frameworks, each requiring only temperature as a Pressure because the vast majority of the relevant studies only investigated changes in temperature, with only a handful examining more than one variable simultaneously. We also specify the change in temperature as an increase to reflect the literature. Finally, we combined multiple services into one box where the references for those services were the same due to their direct ecological connection (e.g. crop pollination and crop yield). The paucity of studies investigating factors other than temperature, clearly indicates that there are knowledge gaps for each focal group relating to the impacts of precipitation, extreme weather events, and temperature simultaneously.

3.2.1 Pollinators

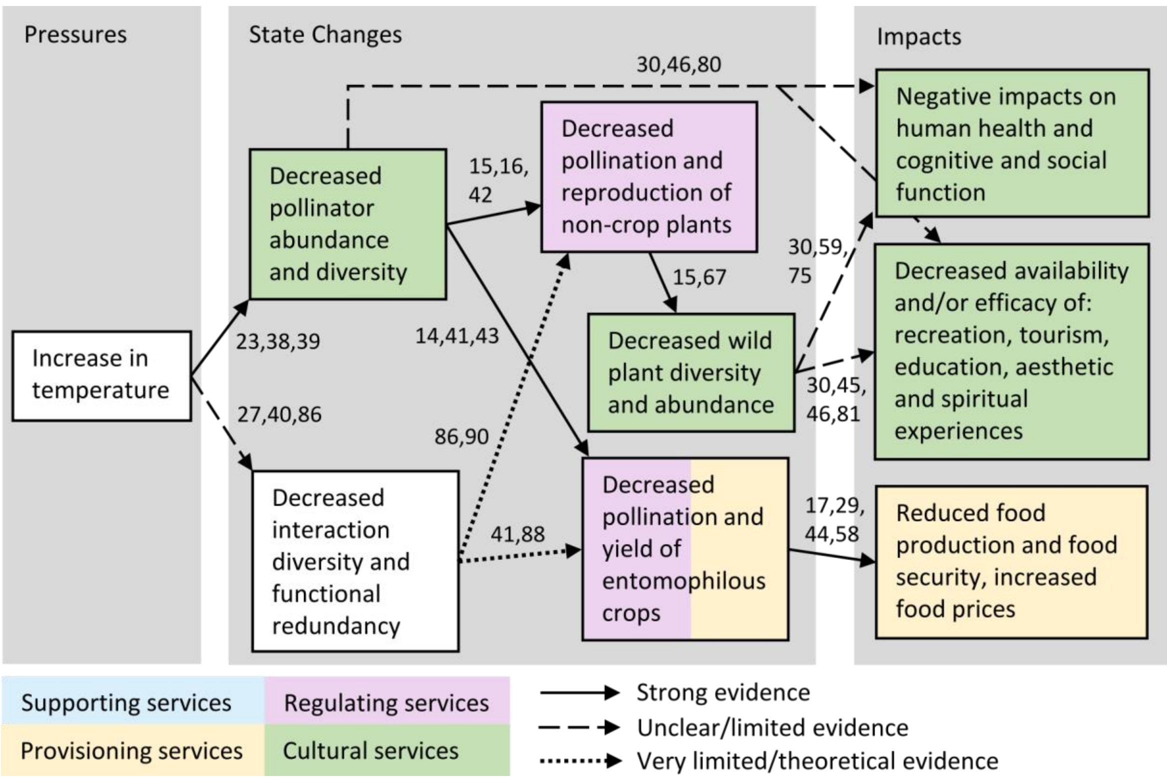

Figure 2 A detailed examination of how temperature increase affects the ecosystem services provided by pollinating insects. Evidence strength is described in Table 1. Numbers represent references detailed in Table S2.

Despite the fact that pollinating insects are a well-studied group, the literature search identified several knowledge gaps surrounding species interactions and cultural services. There is insufficient evidence describing the effects that climate change will have on species interactions at the community-level, particularly how changes in community composition and phenology may affect interaction diversity and functional redundancy (how robust a community is to loss of species depends on other species in the community being able to fulfil the same functional roles, e.g. if all plant species in a given community interact with many different pollinator species, then it has high interaction diversity and functional redundancy) (Figure 2). There is also great uncertainty regarding how any such community-scale changes may affect pollination services, and while several papers suggest a link, only one assesses the impact of reduced functional diversity (Figure 2). Another gap identified relates to non-bee insects such as hoverflies, wasps, and moths, which are increasingly recognised as important pollinators, but the impacts of climate change are absent in the literature (Senapathi et al., 2017).

Cultural ecosystem services are difficult to quantify due to their complicated and context-specific nature (MEA, 2005), leading to zero coverage of how these services alter under climate change. However, given that climate change negatively affects biodiversity and habitats (Brown et al., 2016; Parmesan, 2006), we can use the growing body of evidence that links high diversity and abundance of various species and habitats to cultural service delivery, thus inferring a reduction in cultural services due to a loss of species and habitats (Figures 2, 3 and 4). While there is currently no direct evidence linking pollinator abundance and diversity to cultural services, there is indirect evidence from studies demonstrating a link to wild plant diversity, which we know is dependent on pollinators. Given the charismatic nature of many pollinator species and their importance to human education, recreation, and inspiration (IPBES, 2016), it seems likely that detrimental impacts on pollinator populations will have negative consequences for many cultural services and benefits.

3.2.2 Pest regulators

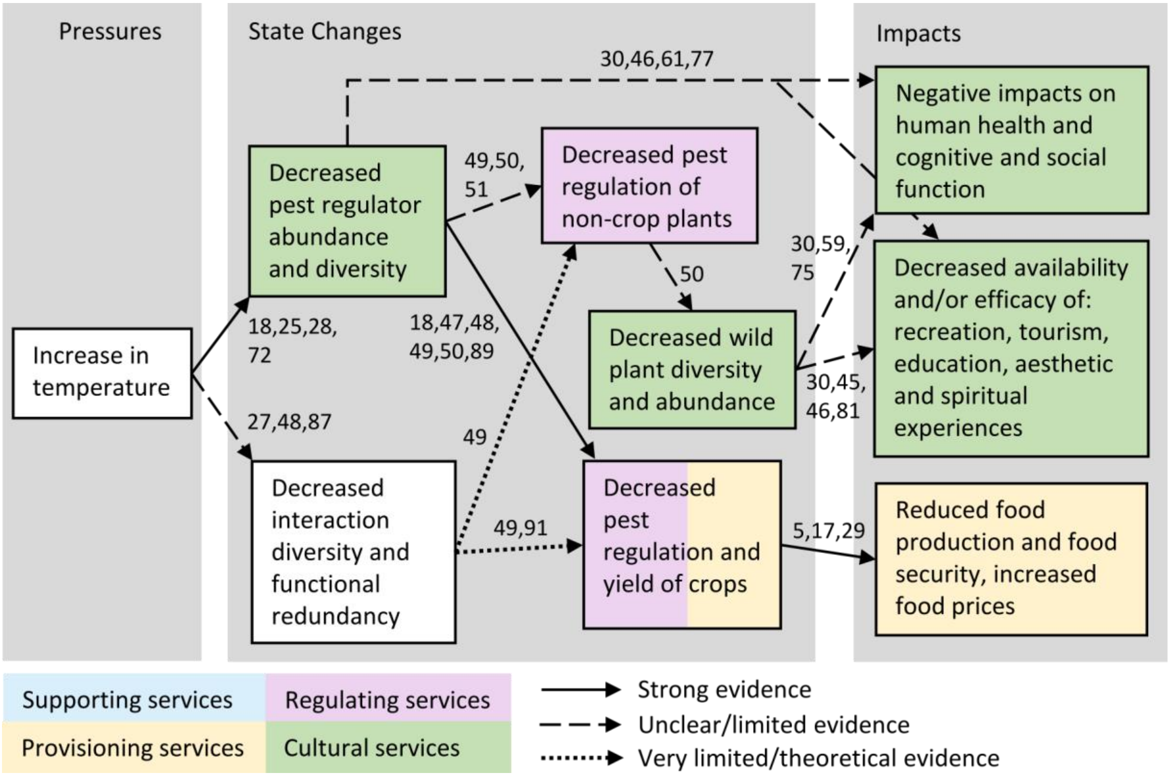

Figure 3 A detailed examination of how temperature increase affects the ecosystem services provided by pest regulating animals. Evidence strength is described in Table 1. Numbers represent references detailed in Table S2.

Figures 2 and 3 are structurally very similar, which is probably due to the relatedness of the most influential group of UK pollinators (bees) to that of pest regulators (wasps) and the species overlap (many pest regulating insects are also pollinators due to the nectar diet of their adult stages). There is a strong body of research covering various aspects of natural pest control by the different animals that provide this service, which includes insectivorous birds, parasitoid and predatory wasps, predatory beetles, and other insects. However, there are several areas with poor evidence. There was little evidence detailing how the abundance and diversity of pest regulators affects pest regulation of non-crop plants and the resulting impacts on wild plant populations (Figure 3). Few published papers investigate the impacts of climate change on community-level interaction diversity and functional redundancy, and most of these only examine one type of pest regulating animal (Figure 3). There is, again, considerable uncertainty regarding how any changes in these species interactions at the community-scale might affect pest regulation services for both crop and non-crop plants (Figure 3). Another key finding was a noticeable focus in the research on parasitoid wasps, while the relationships of other animal groups are less well understood.

As with pollinators, there was a clear knowledge gap relating to the delivery of cultural services by pest regulating organisms. The indirect link to cultural services via wild plant diversity and abundance is weaker here than for pollinators, given the previously mentioned lack of focus on non-crop plants, but there is some evidence specifically linking the abundance and diversity of birds to some cultural services (Figure 3).

3.2.3 Arbuscular mycorrhizal fungi (AMF)

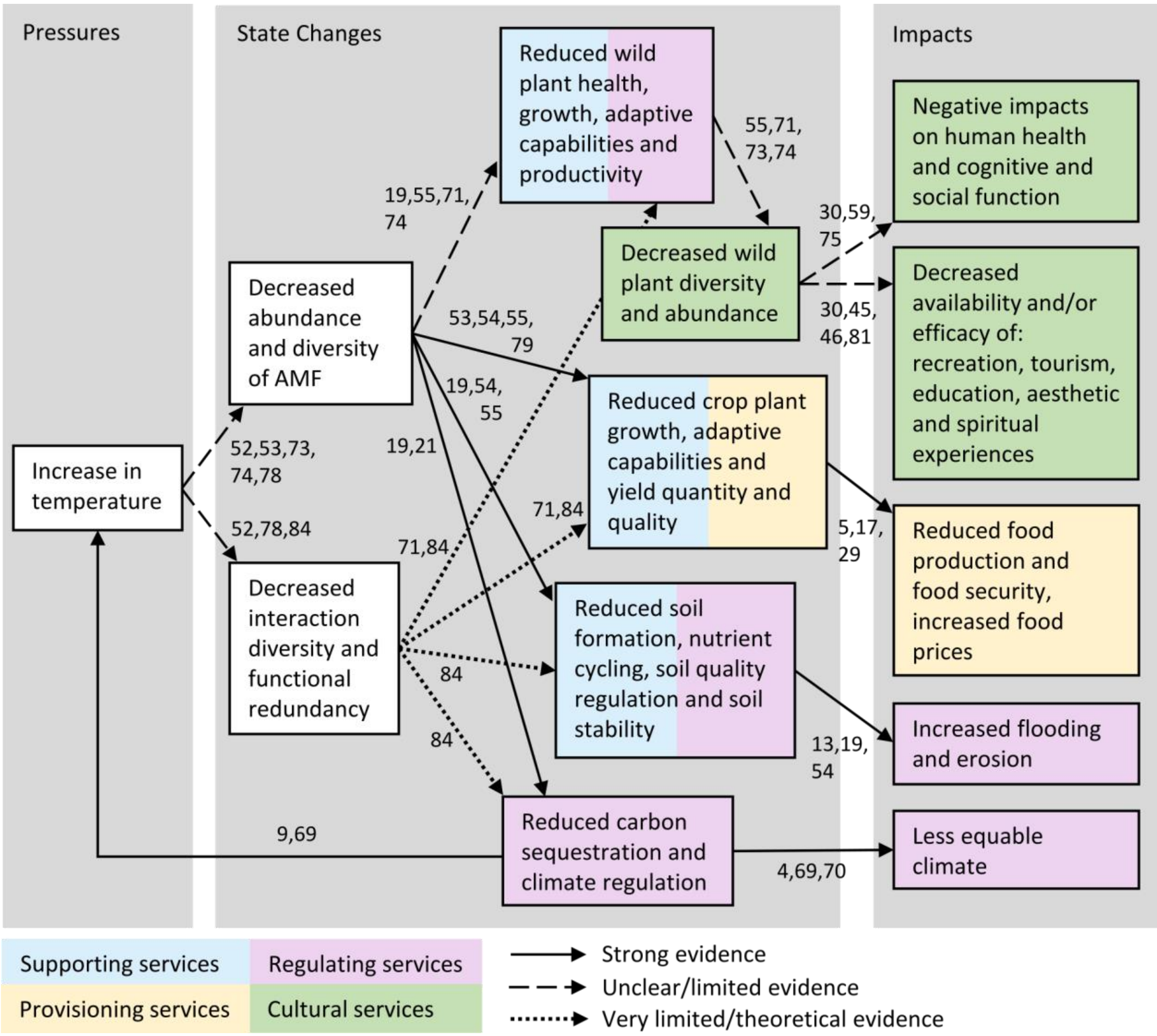

Figure 4 A detailed examination of how temperature increase affects the ecosystem services provided by AMF (arbuscular mycorrhizal fungi). Evidence strength is described in Table 1. Numbers represent references detailed in Table S2.

Due to the complexity of the interactions between arbuscular mycorrhizal fungi (AMF), host plants, and the abiotic environment, it is more difficult to isolate specific relationships and impacts on ecosystem service delivery in relation to AMF, than for pollinators or pest regulators (Tylianakis et al., 2008). AMF also contribute to a relatively large number of ecosystem services, with many more knowledge gaps than for the other organism groups. There was little evidence describing the effects of climate change on the delivery of services to non-crop plants and the consequent impacts on their diversity and abundance (Figure 4). Evidence detailing the effects of climate change on community-scale plant-AMF interaction diversity was also lacking (Figure 4), and there is considerable uncertainty regarding how any such changes may go on to impact AMF service provision (Figure 4). Finally, there is also a lack of consensus in the literature regarding how the abundance and diversity of this organism group may be directly affected by climate warming (Figure 4).

3.3 Step 3: Directional trends under projected climate scenarios for the 21st century

We assessed the expected directional trends for each of the climate change Pressures, State changes, and Impacts reported in the initial DPSIR framework (Figure 1), based upon the current literature and climate projections (Figure 5) (IPCC, 2013; Lowe et al., 2018). Almost all elements in the State change and Impacts categories will likely experience negative directional trends as a result of climate change (Figure 5). Although it is worth noting some uncertainties (grey and white arrows) stemming from knowledge gaps around soil features and related below-ground services, cultural services and nature related benefits, and species interaction diversity (see section 3.2).

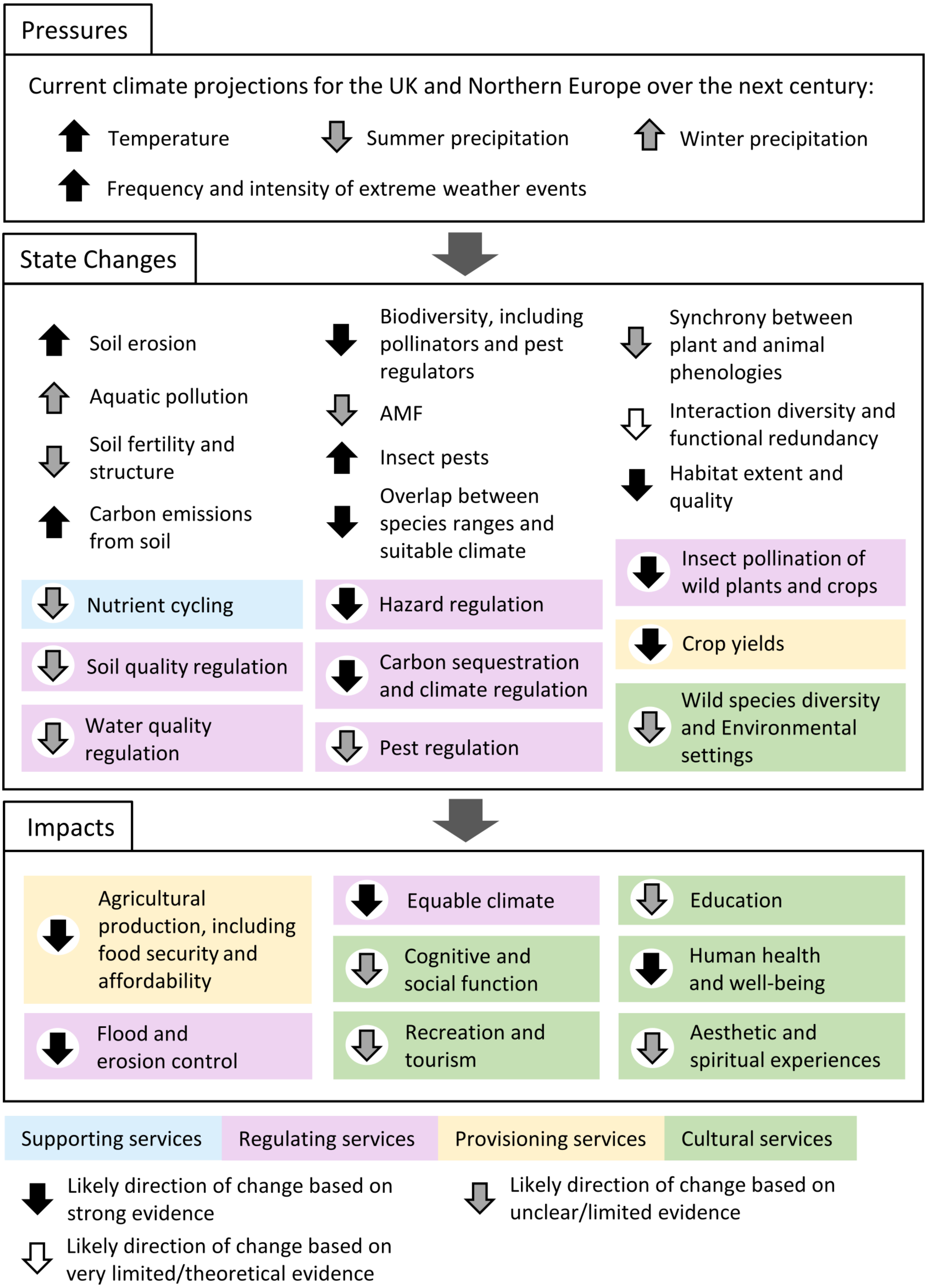

Figure 5 Directional trends for the Pressures, State Changes, and Impacts in the DPSIR (Figure 1) based on IPCC and Met Office climate change projections, and current dominant understandings in the literature (for references see Figure 1 and Table S2).

4 Discussion

We have demonstrated the DPSIR framework as an effective tool for structuring evidence about climate change and agro-ecosystem functioning from varied sources across many disciplines. Our framework was able to capture the system-wide consequences of climate change and display the pathways between the environmental and societal features of UK agro-ecosystems, at a broad scale. We extended the framework to explore focal pathways in greater detail and highlight important knowledge gaps, and also provide an overview of the directionality of specific changes for each feature.

4.1 The DPSIR framework

Construction of the framework was initially hindered by inconsistencies of approach with respect to how the DPSIR is applied to systems and ecosystem services. For example, some authors consider both environmental and societal aspects of the system within Impacts (Bär et al., 2015; Omann et al., 2009), while others only consider the societal aspects (Elliott et al., 2017). Such discrepancies have been detailed by Gari et al. (2015), who also provide some 'best practice' recommendations that aim to promote consistency across DPSIR applications. Placement of different agro-ecosystem features within the framework was also complicated by the different ecosystem service classifications employed in the wider literature (La Notte et al., 2017). For example, socio-economic literature often downplays supporting services (e.g. soil formation) by combining them into a collection of functions termed 'ecosystem processes' (Spangenberg et al., 2014; TEEB, 2010). Whilst we were able to account for these difficulties, they serve to highlight the wider need for greater consistency between disciplines with regards to the definitions and classification systems used.

4.2 Knowledge gaps

Drawing on evidence from the literature to create the DPSIR framework provided insight into the knowledge gaps that exist within that literature. While identifying and emphasizing these gaps is a positive step towards addressing them, it is also useful to contextualise them so that we can understand why they exist. Such discussions can facilitate these gaps becoming future research priorities, which can ultimately lead to more informed and effective policy (UNEP, 2019).

Many of the highlighted knowledge gaps relate to how climate change is expected to affect species interactions at the level of the community, and how this in turn may affect the delivery of ecosystem services. Studying community-wide species interactions can be very challenging due to the resource-intensive methods required, particularly if research is undertaken in-situ and especially for organisms that are difficult to detect and identify, such as parasitoid wasps and soil fungi (Evans et al., 2016). Combining DNA metabarcoding approaches with network analysis represents a promising contemporary method of investigating these interactions and their impacts upon ecosystem functioning (Derocles et al., 2018; Evans et al., 2016). However, even with modern methods it can be difficult to identify causal links between climate change and changes in species interactions, due to the complicated nature of the relationships between the different environmental variables and species. Often the results of studies investigating the same topic using different methodologies do not align (Hegland et al., 2009; Tylianakis et al., 2008). Measuring ecosystem service provision has also proved difficult, as we cannot assume that every interaction equates to service delivery (Ballantyne et al., 2015). Another key issue highlighted in the DPSIR is a lack of research investigating how simultaneous changes in multiple climatic variables will affect agro-ecosystem biodiversity and ecosystem services. This is most likely due to the practicalities involved. Field experiments simulating increases in temperature can be logistically and financially difficult at large scales, and while laboratory experiments can more easily simulate all the relevant variables, they are unable to include the complete native organism communities, and so cannot capture the full ecosystem consequences (Derocles et al., 2018).

Many of the knowledge gaps we identified relate to the links between biodiversity and cultural services. At present, there is little or no evidence linking the diversity and abundance of specific agro-ecosystem organisms, such as pollinating insects, to cultural services and benefits. While there are some studies describing positive relationships linking plant diversity and biodiversity more generally to a range of cultural services, there are no studies investigating how biodiversity loss may impact them. The apparent lack of attention afforded to cultural service research could be due to the interdisciplinary nature of the topic, given that it requires social and natural scientists work together; a recognised challenge in the broader scientific domain that is showing some modest signs of improving (Noorden, 2015). Interest in cultural service research is increasing, so it is probable that the focus will broaden in the near future to encompass more organism groups and to include experiments and hypothesis testing relating to environmental change.

4.3 Directional trends

Managing agro-ecosystems to support multiple ecosystem services in the face of environmental change is a complex challenge. Effective policy creation requires accessible syntheses and visualisations of scientific evidence that incorporate uncertainty (Lescourret et al., 2015). To this end, we provide a clear summary of how climate change could impact UK agro-ecosystem biodiversity and ecosystem services, based on current evidence (Figure 5). It is likely that many of the services associated with agro-ecosystems will be down-regulated, causing a decline in the availability of the associated goods and benefits. The evidence for negative effects upon biodiversity and habitats is particularly strong and concerning, as is the evidence for increased environmental degradation such as soil erosion (Brown et al., 2016; Parmesan, 2006). Another troubling issue is that of crop yields. There is now strong evidence indicating that yields will decrease significantly as a result of temperature increases (Cai et al., 2015; Liu et al., 2016), but the predicted ecological and environmental degradation, combined with increases in pest organisms and extreme weather events, are extremely likely to further impact food production and security. Yet these predictions are not certainties.

The Response category of the DPSIR framework (Figure 1) contains some key policy documents outlining UK government plans that aim to increase the resilience of the UK's agricultural environments to climate change (DEFRA, 2018; UK Government, 2018), however, detailed plans are not yet available as the new 'Environmental Land Management Scheme' (ELM) is currently under development. The negative impacts that we found on biodiversity, soil quality, crop yields, and a wide variety of ecosystem services and goods suggests that current policy strategies are not working. Therefore, the new ELM should consider a broader range of ecosystem services and environmental features, put greater focus on non-crop biodiversity, and take a more targeted approach to management that includes specific provisions for building resilience to climate change. These principles will ensure that the most vulnerable features of agro-ecosystems are protected. Supporting and promoting agricultural sustainability practices such as agroforestry and conservation agriculture would also improve climate resilience (IPBES, 2019; UNEP, 2019). In practice, this could be achieved using a 'payment for ecosystem services/natural capital' approach that is dependent upon maintaining and improving resilience (UNEP, 2019). While these policies would focus on mitigating the impacts of climate change, many could also contribute to climate change prevention via increased carbon storage. However, tackling CO_2 emissions requires attention beyond agro-ecosystems, such as renewable energy and addressing societal behaviour (e.g. food waste and meat consumption), and demands a global scale.

4.4 Limitations

We constructed our DPSIR framework using a literature review approach and the combined expertise of a limited multidisciplinary team (two ecologists and one environmental economist). It could be argued that a broader disciplined team may have identified additional relevant relationships that we were unable to detect. We attempted to counter this limitation by accessing literature with a broad scope compiled by large multidisciplinary teams such as the MEA, UK NEA, and UK Government climate change risk assessment reports (Brown et al., 2016; Knox et al., 2012; MEA, 2005; UK NEA, 2011).

5 Conclusions

Food security and biodiversity loss are serious and potentially conflicting problems that cannot easily be resolved, particularly with the threat of climate change becoming increasingly more urgent. We developed a novel three-step approach that allowed exploration of the climate change impacts on UK agro-ecosystems at both broad and fine scales. The DPSIR constructed in this study has identified several topics that require further investigation, including the impacts that climate change will have on community interactions across trophic levels and the resulting changes to ecosystem service delivery. The knowledge gaps identified here represent opportunities that researchers and funding organisations need to capitalise on – addressing these issues would provide a stronger case for biodiversity conservation and sustainable management of agro-ecosystems. Our analyses also provide directionality to future climate impacts on key aspects of our biodiversity and ecosystem services. When faced with understanding a system with multiple interacting factors it is easy to become paralysed by complexity. We provide a simplification of this important system under climate change to help direct future evidence gathering and affect positive change.

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Authors' Contributions

DM and JA conceived the research idea. EM developed the methodology and conducted the literature review. EM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

CRediT author statement:

Ellen Moss: Methodology, Investigation, Visualisation, Writing – Original Draft. **Darren Evans:** Conceptualisation, Writing – Review and Editing. **Jonathan Atkins:** Conceptualisation, Writing – Review and Editing.

Declarations of interest

None.

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services — A global review. Geoderma 262, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009

Ballantyne, G., Baldock, K.C.R., Willmer, P.G., 2015. Constructing more informative plant–pollinator networks: visitation and pollen deposition networks in a heathland plant community. Proc. R. Soc. B 282, 20151130. https://doi.org/10.1098/rspb.2015.1130

Bär, R., Rouholahnejad, E., Rahman, K., Abbaspour, K.C., Lehmann, A., 2015. Climate change and agricultural water resources: A vulnerability assessment of the Black Sea catchment. Environmental Science & Policy 46, 57–69. https://doi.org/10.1016/j.envsci.2014.04.008

Bebber, D.P., Holmes, T., Gurr, S.J., 2014. The global spread of crop pests and pathogens. Global Ecology and Biogeography 23, 1398–1407. https://doi.org/10.1111/geb.12214

Brown, I., Thompson, D., Bardgett, R., Berry, P., Crute, I., Morison, J., Morecroft, M., Pinnegar, J., Reeder, T., Topp, K., 2016. UK Climate Change Risk Assessment Evidence Report: Chapter 3, Natural Environment and Natural Assets. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Cai, C., Yin, X., He, S., Jiang, W., Si, C., Struik, P.C., Luo, W., Li, G., Xie, Y., Xiong, Y., Pan, G., 2015. Responses of wheat and rice to factorial combinations of ambient and elevated CO2 and temperature in FACE experiments. Global Change Biology 22, 856–874. https://doi.org/10.1111/gcb.13065

Cardinale, B.J., Harvey, C.T., Gross, K., Ives, A.R., 2003. Biodiversity and biocontrol: emergent impacts of a multi-enemy assemblage on pest suppression and crop yield in an agroecosystem. Ecology Letters 6, 857–865. https://doi.org/10.1046/j.1461-0248.2003.00508.x

DEFRA, 2018. The national adaptation programme: Making the country resilient to a changing climate. DEFRA, United Kingdom.

Derocles, S.A.P., Lunt, D.H., Berthe, S.C.F., Nichols, P.C., Moss, E.D., Evans, D.M., 2018. Climate-warming alters the structure of farmland tri-trophic ecological networks and reduces crop yield. Molecular Ecology 27, 4931–4946. https://doi.org/10.1111/mec.14903

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - A unifying framework for marine environmental management. Marine Pollution Bulletin 118, 27–40. https://doi.org/10.1016/j.marpolbul.2017.03.049

Evans, D.M., Kitson, J.J.N., Lunt, D.H., Straw, N.A., Pocock, Michael.J.O., 2016. Merging DNA metabarcoding and ecological network analysis to understand and build resilient terrestrial ecosystems. Functional Ecology 30, 1904–1916. https://doi.org/10.1111/1365-2435.12659

Gabrielsen, P., Bosch, P., 2003. Environmental indicators: Typology and Use in Reporting (Technical Report). European Environment Agency.

Gari, S.R., Newton, A., Icely, J.D., 2015. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean & Coastal Management 103, 63–77. https://doi.org/10.1016/j.ocecoaman.2014.11.013

Gianinazzi, S., Gollotte, A., Binet, M.-N., Tuinen, D. van, Redecker, D., Wipf, D., 2010. Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza 20, 519–530. https://doi.org/10.1007/s00572-010-0333-3

Gosling, P., Hodge, A., Goodlass, G., Bending, G.D., 2006. Arbuscular mycorrhizal fungi and organic farming. Agriculture, Ecosystems & Environment 113, 17–35. https://doi.org/10.1016/j.agee.2005.09.009

Harrington, R., Clark, S.J., Welham, S.J., Verrier, P.J., Denholm, C.H., Hullé, M., Maurice, D., Rounsevell, M.D., Cocu, N., Consortium, E.U.E., 2007. Environmental change and the phenology of European aphids. Global Change Biology 13, 1550–1564. https://doi.org/10.1111/j.1365-2486.2007.01394.x

Hegland, S.J., Nielsen, A., Lázaro, A., Bjerknes, A.-L., Totland, Ø., 2009. How does climate warming affect plant-pollinator interactions? Ecology Letters 12, 184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x

Holman, I.P., Rounsevell, M.D.A., Cojacaru, G., Shackley, S., McLachlan, C., Audsley, E., Berry, P.M., Fontaine, C., Harrison, P.A., Henriques, C., Mokrech, M., Nicholls, R.J., Pearn, K.R., Richards, J.A., 2008. The concepts and development of a participatory regional integrated assessment tool. Climatic Change 90, 5–30. https://doi.org/10.1007/s10584-008-9453-6

Hooper, T., Beaumont, N., Griffiths, C., Langmead, O., Somerfield, P.J., 2017. Assessing the sensitivity of ecosystem services to changing pressures. Ecosystem Services 24, 160–169. https://doi.org/10.1016/j.ecoser.2017.02.016

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. IPBES Secretariat, Bonn, Germany.

IPBES, 2016. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. IPBES Secretariat, Bonn, Germany.

IPCC, 2014. Climate Change 2014: Working Group II: Impacts, Adaptation, and Vulnerability. Summary for Policy Makers. (Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). Intergovernmental Panel on Climate Change, Switzerland.

IPCC, 2013. Climate Change 2013: Working Group I: The Physical Science Basis. Summary for Policy Makers. (Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). Intergovernmental Panel on Climate Change, Switzerland.

Kelble, C.R., Loomis, D.K., Lovelace, S., Nuttle, W.K., Ortner, P.B., Fletcher, P., Cook, G.S., Lorenz, J.J., Boyer, J.N., 2013. The EBM-DPSER Conceptual Model: Integrating Ecosystem Services into the DPSIR Framework. PLoS ONE 8, e70766. https://doi.org/10.1371/journal.pone.0070766

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. B 274, 303–313. https://doi.org/10.1098/rspb.2006.3721

Knox, J.W., Hurford, A., Hargreaves, L., Wall, E., 2012. Defra Project GA0204. Climate Change Risk Assessment for the Agriculture Sector. DEFRA.

La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossman, N.D., 2017. Ecosystem services classification: A systems ecology perspective of the cascade framework. Ecological Indicators 74, 392–402. https://doi.org/10.1016/j.ecolind.2016.11.030

Lescourret, F., Magda, D., Richard, G., Adam-Blondon, A.-F., Bardy, M., Baudry, J., Doussan, I., Dumont, B., Lefèvre, F., Litrico, I., Martin-Clouaire, R., Montuelle, B., Pellerin, S., Plantegenest, M., Tancoigne, E., Thomas, A., Guyomard, H., Soussana, J.-F., 2015. A social–ecological approach to managing multiple agro-ecosystem services. Current Opinion in Environmental Sustainability 14, 68–75. https://doi.org/10.1016/j.cosust.2015.04.001

Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D.B., Martre, P., Ruane, A.C., Wallach, D., Jones, J.W., Rosenzweig, C., Aggarwal, P.K., Alderman, P.D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., Sanctis, G.D., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Kimball, B.A., Koehler, A.-K., Kumar, S.N., Nendel, C., O'Leary, G., Olesen, J.E., Ottman, M.J., Palosuo, T., Prasad, P.V.V., Priesack, E., Pugh, T.A.M., Reynolds, M., Rezaei, E.E., Rötter, R.P., Schmid, E., Semenov, M.A., Shcherbak, I., Stehfest, E., Stöckle, C.O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wall, G.W., Wang, E., White, J.W., Wolf, J., Zhao, Z., Zhu, Y., 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. Nature Climate Change 6, 1130–1136. https://doi.org/10.1038/nclimate3115

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G., Howard, T., Kaye, N., Kendon, E., Krijnen, J., Maisey, P., McDonald, R., McInnes, R., McSweeney, C., Mitchell, J.F.B., Murphy, J., Palmer, M., Roberts, C., Rostron, J., Sexton, D., Thornton, H., Tinker, J., Tucker, S., Yamazaki, K., Belcher, S., 2018. UKCP18 UK Climate Projections Science Overview Report. Met Office Hadley Centre, Exeter.

Manhães, A.P., Loyola, R., Mazzochini, G.G., Ganade, G., Oliveira-Filho, A.T., Carvalho, A.R., 2018. Low-cost strategies for protecting ecosystem services and biodiversity. Biological Conservation 217, 187–194. https://doi.org/10.1016/j.biocon.2017.11.009

MEA, 2005. The Millennium Ecosystem Assessment: Current State & Trends Assessment. World Resources Institute, Washington, DC.

Mosaffaie, J., Salehpour Jam, A., Tabatabaei, M.R., Kousari, M.R., 2021. Trend assessment of the watershed health based on DPSIR framework. Land Use Policy 100, 104911. https://doi.org/10.1016/j.landusepol.2020.104911

Noorden, R.V., 2015. Interdisciplinary research by the numbers. Nature 525, 306–307. https://doi.org/10.1038/525306a

Omann, I., Stocker, A., Jäger, J., 2009. Climate change as a threat to biodiversity: An application of the DPSIR approach. Ecological Economics 69, 24–31. https://doi.org/10.1016/j.ecolecon.2009.01.003

Östman, Ö., Ekbom, B., Bengtsson, J., 2003. Yield increase attributable to aphid predation by ground-living polyphagous natural enemies in spring barley in Sweden. Ecological Economics 45, 149–158. https://doi.org/10.1016/S0921-8009(03)00007-7

Parmesan, C., 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics 37, 637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100
Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421, 37–42. https://doi.org/10.1038/nature01286
Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14, 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008
Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Phil. Trans. R. Soc. B 365, 2959–2971. https://doi.org/10.1098/rstb.2010.0143
Rounsevell, M.D.A., Dawson, T.P., Harrison, P.A., 2010. A conceptual framework to assess the effects of environmental change on ecosystem services. Biodiversity and Conservation 19, 2823–2842. https://doi.org/10.1007/s10531-010-9838-5
Senapathi, D., Goddard, M.A., Kunin, W.E., Baldock, K.C.R., 2017. Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. Functional Ecology 31, 26–37. https://doi.org/10.1111/1365-2435.12809
Smith, S.E., Read, D.J., 2008. Mycorrhizal Symbioses, 3rd Edition. ed. Academic Press, London.
Spangenberg, J.H., von Haaren, C., Settele, J., 2014. The ecosystem service cascade: Further developing the metaphor. Integrating societal processes to accommodate social processes and planning, and the case of bioenergy. Ecological Economics 104, 22–32. https://doi.org/10.1016/j.ecolecon.2014.04.025
TEEB, 2010. The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Routledge, Abingdon, UK.
Tscherning, K., Helming, K., Krippner, B., Sieber, S., Paloma, S.G. y, 2012. Does research applying the DPSIR framework support decision making? Land Use Policy 29, 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009
Tylianakis, J.M., Didham, R.K., Bascompte, J., Wardle, D.A., 2008. Global change and species interactions in terrestrial ecosystems. Ecology Letters 11, 1351–1363. https://doi.org/10.1111/j.1461-0248.2008.01250.x
UK Government, 2018. A Green Future: Our 25 Year Plan to Improve the Environment.
UK NEA, 2011. The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge.
UNEP, 2019. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. UN Environment Programme, Nairobi, Kenya.
Whelan, C.J., Wenny, D.G., Marquis, R.J., 2008. Ecosystem Services Provided by Birds. Annals of the New York Academy of Sciences 1134, 25–60. https://doi.org/10.1196/annals.1439.003

Supplementary Material

Ecosystem service framework

The ecosystem service framework employed in this study. It was able to: accommodate the different classification systems employed by the evidence collected during the literature search; integrate well with the structure of the DPSIR framework; and reduce the likelihood of errors relating to double-counting, omitting, or misplacement of elements within the DPSIR framework.

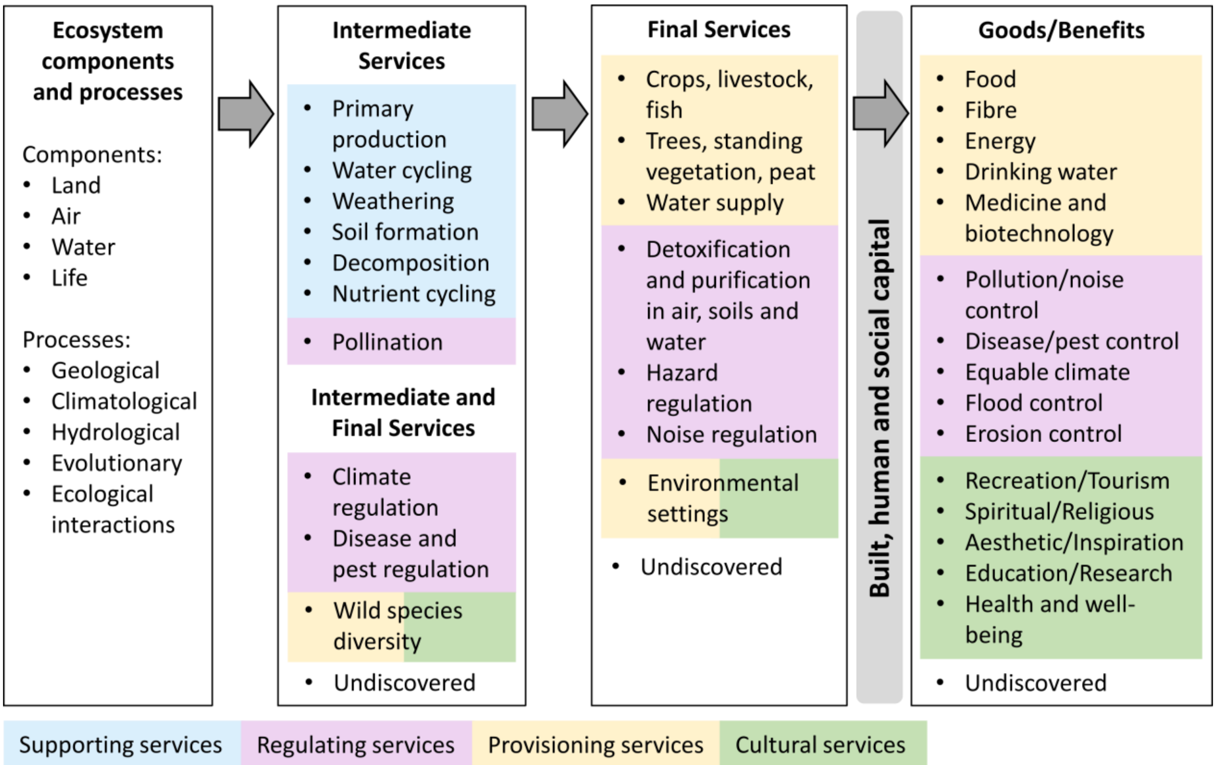

Figure S1 The Ecosystem Service Framework: ecosystem processes, intermediate and final ecosystem services, and goods/benefits used in the UK NEA (adapted from Figure 2.3, UK National Ecosystem Assessment Technical Report).

It is important to note that the classification of a service can be dependent on the system or research question; for example, wild species diversity could be intermediate when considering how wild crop plant relatives could support future crop production, or final when considering the cultural services and benefits that wild plants provide (UK NEA, 2011). This context-dependant classification of services is particularly relevant here, given that it could affect the placement of elements within the DPSIR framework.

Literature search

The academic literature search initially started with a relatively small list of search terms that were based on the most obvious Drivers and Pressures, in combination with the three organism groups. This generated most of the literature that populated the State change part of the DPSIR. However, the list of terms evolved and increased over time, as more aspects of the system were identified as relevant to the research. The Impacts category was also populated using a second search strategy, whereby some of the search terms relating to State changes where combined with search terms relating to cultural services. This was to identify any literature demonstrating an indirect link between the Drivers and Pressures and cultural services, via any impact it might have on biodiversity and habitats.

Direct links to climate change	
1st term	**2nd term**
Climate change / warming CO2 Temperature Precipitation / rainfall Drought Heatwave Storm	Ecosystem service(s) Biodiversity / species diversity Pollination / pollinator(s) Pest regulation / pest regulator(s) / natural enemy(s) / IPM / integrated pest management / conservation biological control Arbuscular mycorrhizal fungi / AMF Habitat Species interaction(s) Crop yield(s) Food production / security Cultural service(s) Human health / wellbeing Education Recreation Tourism
Indirect links to climate change	
1st term	**2nd term**
Biodiversity / species diversity Pollination / pollinator(s) Pest regulation / pest regulator(s) Arbuscular mycorrhizal fungi / AMF Habitat Species interaction(s)	Cultural service(s) Human health / wellbeing Education Recreation Tourism

Table S1 Summary of the search terms used for the literature search.

References

Numbered references used in Figures 1, 2, 3 and 4 (displayed over 4 pages).

NB – missing numbers represent references that were no longer necessary in the final version of the framework and so were removed.

4	Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., et al. (2009). UK Climate Projections Science Report: Climate change projections. (Met Office Hadley Centre, Exeter).
5	Asseng, S., Ewert, F., Martre, P., Rötter, R.P., Lobell, D.B., Cammarano, D., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., et al. (2015). Rising temperatures reduce global wheat production. Nature Clim. Change *5*, 143–147.
9	Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., and Kirk, G.J.D. (2005). Carbon losses from all soils across England and Wales 1978–2003. Nature *437*, 245–248.
10	Cannon, R.J.C. (1998). The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. Global Change Biology *4*, 785–796.
11	Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., and Thomas, C.D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science *333*, 1024–1026.
13	Brown, I., Thompson, D., Bardgett, R., Berry, P., Crute, I., Morison, J., Morecroft, M., Pinnegar, J., Reeder, T., and Topp, K. (2016). UK Climate Change Risk Assessment Evidence Report: Chapter 3, Natural Environment and Natural Assets (Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.).
14	Garratt, M.P.D., Breeze, T.D., Boreux, V., Fountain, M.T., McKerchar, M., Webber, S.M., Coston, D.J., Jenner, N., Dean, R., Westbury, D.B., et al. (2016). Apple Pollination: Demand Depends on Variety and Supply Depends on Pollinator Identity. PLOS ONE *11*, e0153889.
15	Lundgren, R., Lázaro, A., and Totland, Ø. (2015). Effects of experimentally simulated pollinator decline on recruitment in two European herbs. J Ecol *103*, 328–337.
16	Kudo, G., and Ida, T.Y. (2013). Early onset of spring increases the phenological mismatch between plants and pollinators. Ecology *94*, 2311–2320.
17	Gregory, P.J., Ingram, J.S.I., and Brklacich, M. (2005). Climate change and food security. Philosophical Transactions of the Royal Society of London B: Biological Sciences *360*, 2139–2148.
18	Romo, C.M., and Tylianakis, J.M. (2013). Elevated Temperature and Drought Interact to Reduce Parasitoid Effectiveness in Suppressing Hosts. PLoS ONE *8*, e58136.
19	Wilson, G.W.T., Rice, C.W., Rillig, M.C., Springer, A., and Hartnett, D.C. (2009). Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments. Ecology Letters *12*, 452–461.
20	Jansa, J., Wiemken, A., and Frossard, E. (2006). The effects of agricultural practices on arbuscular mycorrhizal fungi. Geological Society, London, Special Publications *266*, 89–115.
21	Hawkes, C.V., Hartley, I.P., Ineson, P., and Fitter, A.H. (2008). Soil temperature affects carbon allocation within arbuscular mycorrhizal networks and carbon transport from plant to fungus. Global Change Biology *14*, 1181–1190.
22	Cheng, L., Booker, F.L., Tu, C., Burkey, K.O., Zhou, L., Shew, H.D., Rufty, T.W., and Hu, S. (2012). Arbuscular Mycorrhizal Fungi Increase Organic Carbon Decomposition Under Elevated CO2. Science *337*, 1084–1087.

23	Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W.E. (2010). Global pollinator declines: trends, impacts and drivers. Trends in Ecology & Evolution *25*, 345–353.
24	Macfadyen, S., Gibson, R., Polaszek, A., Morris, R.J., Craze, P.G., Planqué, R., Symondson, W.O.C., and Memmott, J. (2009). Do differences in food web structure between organic and conventional farms affect the ecosystem service of pest control? Ecology Letters *12*, 229–238.
25	Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics *37*, 637–669.
26	Memmott, J., Craze, P.G., Waser, N.M., and Price, M.V. (2007). Global warming and the disruption of plant–pollinator interactions. Ecology Letters *10*, 710–717.
27	Tylianakis, J.M., Didham, R.K., Bascompte, J., and Wardle, D.A. (2008). Global change and species interactions in terrestrial ecosystems. Ecology Letters *11*, 1351–1363.
28	Hance, T., Van Baaren, J., Vernon, P., and Boivin, G. (2006). Impact of extreme temperatures on parasitoids in a climate change perspective. Annual Review of Entomology *52*, 107–126.
29	Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change *14*, 53–67.
30	Sandifer, P.A., Sutton-Grier, A.E., and Ward, B.P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. Ecosystem Services *12*, 1–15.
31	European Commission (2013a). Commission Implementing Regulation (EU) No 485/2013.
32	European Commission (2013b). Overview of CAP Reform 2014-2020.
33	The Committee on Climate Change (2013). Reducing the UK's carbon footprint.
34	Sutherland, W.J., Armstrong-Brown, S., Armsworth, P.R., Tom, B., Brickland, J., Campbell, C.D., Chamberlain, D.E., Cooke, A.I., Dulvy, N.K., Dusic, N.R., et al. (2006). The identification of 100 ecological questions of high policy relevance in the UK. Journal of Applied Ecology *43*, 617–627.
35	European Commission (2011). Our life insurance, our natural capital: an EU biodiversity strategy to 2020.
36	DEFRA (2013). Waste Prevention Programme for England: Priority Areas.
37	European Commission (2012). The 3rd Water Framework Directive Implementation report: River Basin Management Plans 2009-2015.
38	Dormann, C.F., Schweiger, O., Arens, P., Augenstein, I., Aviron, S., Bailey, D., Baudry, J., Billeter, R., Bugter, R., Bukácek, R., et al. (2008). Prediction uncertainty of environmental change effects on temperate European biodiversity. Ecology Letters *11*, 235–244.
39	Fox, R. (2013). The decline of moths in Great Britain: a review of possible causes. Insect Conservation and Diversity *6*, 5–19.
40	Hoiss, B., Krauss, J., and Steffan-Dewenter, I. (2015). Interactive effects of elevation, species richness and extreme climatic events on plant–pollinator networks. Glob Change Biol *21*, 4086–4097.
41	Rogers, S.R., Tarpy, D.R., and Burrack, H.J. (2014). Bee Species Diversity Enhances Productivity and Stability in a Perennial Crop. PLoS ONE *9*, e97307.
42	Jacobs, J.H., Clark, S.J., Denholm, I., Goulson, D., Stoate, C., and Osborne, J.L. (2009). Pollination biology of fruit-bearing hedgerow plants and the role of flower-visiting insects in fruit-set. Ann Bot *104*, 1397–1404.

43	Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., et al. (2013). Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance. Science *339*, 1608–1611.
44	Gallai, N., Salles, J.-M., Settele, J., and Vaissière, B.E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics *68*, 810–821.
45	Quijas, S., Jackson, L.E., Maass, M., Schmid, B., Raffaelli, D., and Balvanera, P. (2012). Plant diversity and generation of ecosystem services at the landscape scale: expert knowledge assessment. Journal of Applied Ecology *49*, 929–940.
46	Mace, G.M., Norris, K., and Fitter, A.H. (2012). Biodiversity and ecosystem services: a multilayered relationship. Trends in Ecology & Evolution *27*, 19–26.
47	Cardinale, B.J., Harvey, C.T., Gross, K., and Ives, A.R. (2003). Biodiversity and biocontrol: emergent impacts of a multi-enemy assemblage on pest suppression and crop yield in an agroecosystem. Ecology Letters *6*, 857–865.
48	Crowder, D.W., and Harwood, J.D. (2014). Promoting biological control in a rapidly changing world. Biological Control *75*, 1–7.
49	Jonsson, M., Kaartinen, R., and Straub, C.S. (2017). Relationships between natural enemy diversity and biological control. Current Opinion in Insect Science *20*, 1–6.
50	Whelan, C.J., Wenny, D.G., and Marquis, R.J. (2008). Ecosystem Services Provided by Birds. Annals of the New York Academy of Sciences *1134*, 25–60.
51	Finke, D.L., and Denno, R.F. (2005). Predator diversity and the functioning of ecosystems: the role of intraguild predation in dampening trophic cascades. Ecology Letters *8*, 1299–1306.
52	Sun, X., Su, Y., Zhang, Y., Wu, M., Zhang, Z., Pei, K., Sun, L., Wan, S., and Liang, Y. (2013). Diversity of arbuscular mycorrhizal fungal spore communities and its relations to plants under increased temperature and precipitation in a natural grassland. Chin. Sci. Bull. *58*, 4109–4119.
53	Tian, B., Yu, Z., Pei, Y., Zhang, Z., Siemann, E., Wan, S., and Ding, J. (2019). Elevated temperature reduces wheat grain yield by increasing pests and decreasing soil mutualists. Pest Management Science *75*, 466–475.
54	Gianinazzi, S., Gollotte, A., Binet, M.-N., Tuinen, D. van, Redecker, D., and Wipf, D. (2010). Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza *20*, 519–530.
55	Smith, S.E., and Read, D.J. (2008). Mycorrhizal Symbioses (Academic Press, London).
56	DEFRA (2014). National Pollinator Strategy.
57	Hardman, C.J., Harrison, D.P.G., Shaw, P.J., Nevard, T.D., Hughes, B., Potts, S.G., and Norris, K. (2015). Supporting local diversity of habitats and species on farmland: a comparison of three wildlife-friendly schemes. J Appl Ecol *53*, 171–180.
58	Gallai, N., and Salles, J.-M. (2016). Adaptation of an economy facing pollinator decline: a prospective analysis from the French case. In Pollination Services to Agriculture: Sustaining and Enhancing a Key Ecosystem Service, B. Gemmill-Herren, ed. (Routledge), pp. 43–56.
59	Fuller, R.A., Irvine, K.N., Devine-Wright, P., Warren, P.H., and Gaston, K.J. (2007). Psychological benefits of greenspace increase with biodiversity. Biology Letters *3*, 390–394.
60	Miller, J.R. (2005). Biodiversity conservation and the extinction of experience. Trends in Ecology & Evolution *20*, 430–434.
61	Booth, J.E., Gaston, K.J., Evans, K.L., and Armsworth, P.R. (2011). The value of species rarity in biodiversity recreation: A birdwatching example. Biological Conservation *144*, 2728–2732.

62	Pastur, G.M., Peri, P.L., Lencinas, M.V., García-Llorente, M., and Martín-López, B. (2015). Spatial patterns of cultural ecosystem services provision in Southern Patagonia. Landscape Ecol *31*, 383–399.
63	DEFRA (2018). The national adaptation programme: Making the country resilient to a changing climate (United Kingdom: DEFRA).
64	DEFRA (2015). Agriculture in the United Kingdom 2014 (DEFRA).
65	Reidsma, P., Ewert, F., Lansink, A.O., and Leemans, R. (2010). Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses. European Journal of Agronomy *32*, 91–102.
66	Haines-Young, R. (2007). Tracking Change in the Character of the English Landscape, 1999–2003. (Natural England).
67	Lundgren, R., Totland, Ø., and Lázaro, A. (2016). Experimental simulation of pollinator decline causes community-wide reductions in seedling diversity and abundance. Ecology *97*, 1420–1430.
68	Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., and Wade, A.J. (2009). A review of the potential impacts of climate change on surface water quality. Hydrological Sciences Journal *54*, 101–123.
69	IPCC (2013). Climate Change 2013: Working Group I: The Physical Science Basis. Summary for Policy Makers. (Switzerland: Intergovernmental Panel on Climate Change).
70	McMichael, A.J., Woodruff, R.E., and Hales, S. (2006). Climate change and human health: present and future risks. The Lancet *367*, 859–869.
71	van der Heijden, M.G.A., Klironomos, J.N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A., and Sanders, I.R. (1998). Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature *396*, 69–72.
72	Lemoine, N., Schaefer, H.-C., and Böhning-Gaese, K. (2007). Species richness of migratory birds is influenced by global climate change. Global Ecology and Biogeography *16*, 55–64.
73	Wilson, H., Johnson, B.R., Bohannan, B., Pfeifer-Meister, L., Mueller, R., and Bridgham, S.D. (2016). Experimental warming decreases arbuscular mycorrhizal fungal colonization in prairie plants along a Mediterranean climate gradient. PeerJ *4*, e2083.
74	Zhang, T., Yang, X., Guo, R., and Guo, J. (2016). Response of AM fungi spore population to elevated temperature and nitrogen addition and their influence on the plant community composition and productivity. Sci Rep *6*.
75	Twohig-Bennett, C., and Jones, A. (2018). The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. Environmental Research *166*, 628–637.
76	UK Government (2017). UK Climate Change Risk Assessment 2017.
77	Belaire, J.A., Westphal, L.M., Whelan, C.J., and Minor, E.S. (2015). Urban residents' perceptions of birds in the neighborhood: Biodiversity, cultural ecosystem services, and disservices. The Condor *117*, 192–202.
78	Shi, G., Yao, B., Liu, Y., Jiang, S., Wang, W., Pan, J., Zhao, X., Feng, H., and Zhou, H. (2017). The phylogenetic structure of AMF communities shifts in response to gradient warming with and without winter grazing on the Qinghai–Tibet Plateau. Applied Soil Ecology *121*, 31–40.
79	Manoharan, L., Rosenstock, N.P., Williams, A., and Hedlund, K. (2017). Agricultural management practices influence AMF diversity and community composition with cascading effects on plant productivity. Applied Soil Ecology *115*, 53–59.

80	Matias, D.M.S., Leventon, J., Rau, A.-L., Borgemeister, C., and Wehrden, H. von (2016). A review of ecosystem service benefits from wild bees across social contexts. Ambio 1–12.
81	Southon, G.E., Jorgensen, A., Dunnett, N., Hoyle, H., and Evans, K.L. (2016). Biodiverse perennial meadows have aesthetic value and increase residents' perceptions of site quality in urban green-space. Landscape and Urban Planning *158*, 105–118.
82	UK Government (2018). A Green Future: Our 25 Year Plan to Improve the Environment.
84	Cotton, T.A. (2018). Arbuscular mycorrhizal fungal communities and global change: an uncertain future. FEMS Microbiology Ecology *94*.
85	Forrest, J.R.K. (2015). Plant–pollinator interactions and phenological change: what can we learn about climate impacts from experiments and observations? Oikos *124*, 4–13.
86	Burkle, L.A., Marlin, J.C., and Knight, T.M. (2013). Plant-Pollinator Interactions over 120 Years: Loss of Species, Co-Occurrence, and Function. Science *339*, 1611–1615.
87	Derocles, S.A.P., Lunt, D.H., Berthe, S.C.F., Nichols, P.C., Moss, E.D., and Evans, D.M. (2018). Climate-warming alters the structure of farmland tri-trophic ecological networks and reduces crop yield. Molecular Ecology *27*, 4931–4946.
88	Kőrösi, Á., Markó, V., Kovács-Hostyánszki, A., Somay, L., Varga, Á., Elek, Z., Boreux, V., Klein, A.-M., Földesi, R., and Báldi, A. (2018). Climate-induced phenological shift of apple trees has diverse effects on pollinators, herbivores and natural enemies. PeerJ *6*, e5269.
89	Evans, E.W., Carlile, N.R., Innes, M.B., and Pitigala, N. (2013). Warm springs reduce parasitism of the cereal leaf beetle through phenological mismatch. Journal of Applied Entomology *137*, 383–391.
90	Kaiser-Bunbury, C.N., Mougal, J., Whittington, A.E., Valentin, T., Gabriel, R., Olesen, J.M., and Blüthgen, N. (2017). Ecosystem restoration strengthens pollination network resilience and function. Nature *542*, 223–227.
91	Drieu, R., and Rusch, A. (2017). Conserving species-rich predator assemblages strengthens natural pest control in a climate warming context. Agricultural and Forest Entomology *19*, 52–59.

Table S2 References used to create the DPSIR framework and the corresponding numbers used to denote them in Figures 1, 2, 3 and 4 (displayed over 4 pages)

Combined Figure

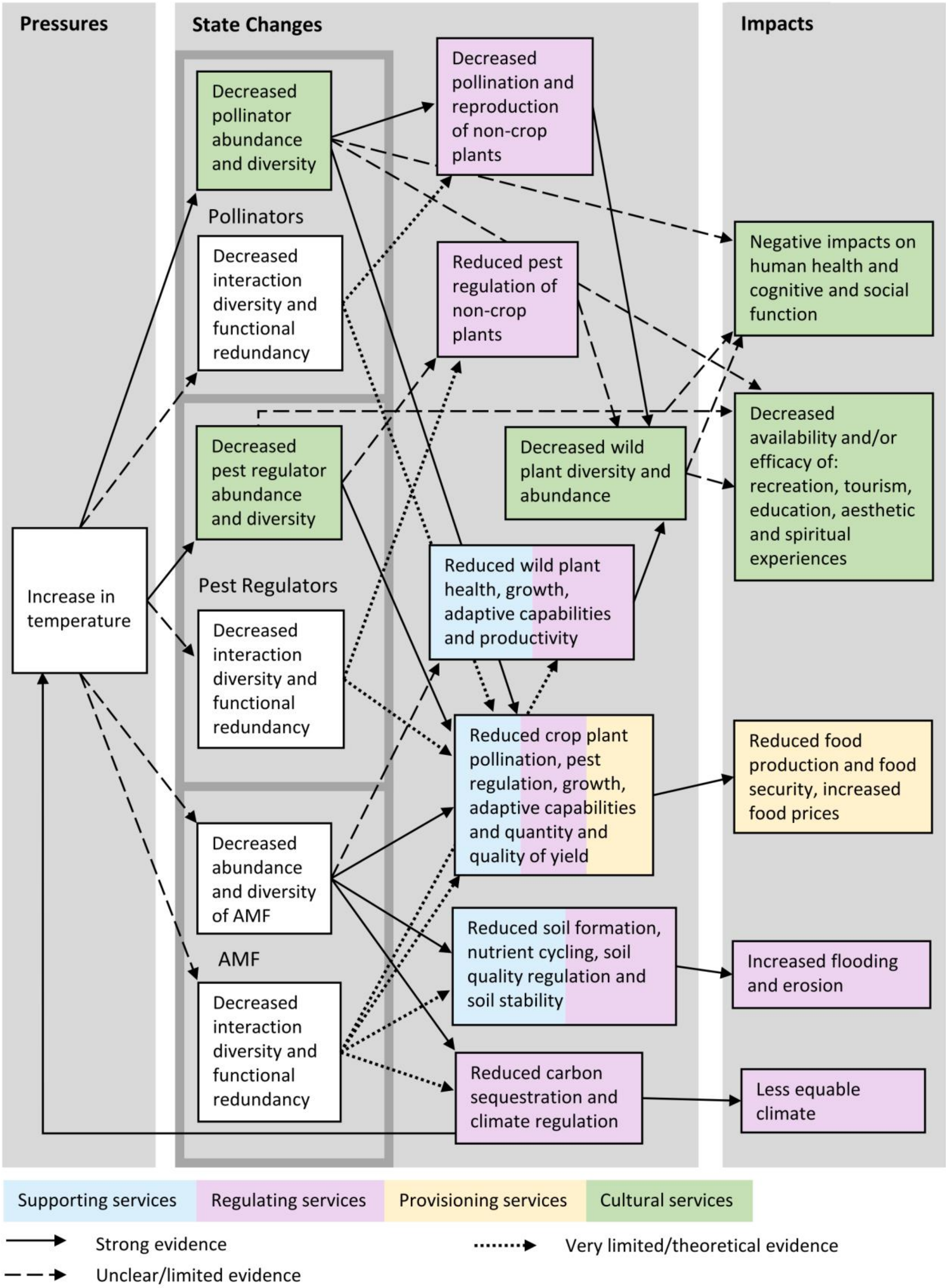

Figure S2 A detailed examination of how climate warming impacts the ecosystem services provided by pollinating insects, pest regulating animals, and AMF. Created by combining Figures 2, 3 and 4.