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2020

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Abstract

We believe that approaches to landscape modification should explicitly include farmers, given their understanding of landscape management practices, and consider climate change, so that the landscapes are designed for future environmental conditions. Climate change is an existential threat to farmers and current patterns of arable agriculture, which will lead to increases in the variability of agricultural productivity and crop failure. The performance of many of the crops that are currently highly productive will decline significantly and the geographical envelopes within which these crops can be grown are expected to shift northwards in Europe. Farmers will likely be faced with a choice: either leave farming or modify the crops that are grown, adopting new cultivars or species able to be cultivated profitably under future climatic conditions. We hypothesised that farmers do not adopt new crops or cultivars individually but use crops within sequences, called rotations, which are agronomically well understood. We know from past research that changes to rotations will lead to changes in biodiversity and the ecosystem services furnished by farmland, both within a field and at landscape scales. Here, we show how we might: use farmer knowledge of crop agronomy to propose future crop rotations in the light of climate change predictions; model these crop rotations to estimate likely effects on economy, biodiversity and ecosystem services; and validate these predictions through empirical study in regions where the rotations are already used. A workflow of co-development would have the benefit of generating practical rotations built on farmer knowledge and demonstrate empirically the predicted economic and ecological effects, markedly increasing the likely credibility of the results for farmers. Such a methodology has the potential to transform future sustainable agricultural landscapes.

1 Introduction

Agriculture is the main source of food for the majority of the world's population. The future of agriculture is therefore essential for food security but increased agricultural land use and agricultural intensification is one of the major drivers of biodiversity decline that can profoundly affect the ecosystem functions that support agricultural productivity and human well-being (IPBES 2019). Much of the current research emphasis on sustainable landscapes have been framed in terms of the debate about pesticides and agricultural intensification that have driven declines in farmland biodiversity (Geiger et al. 2010, Kleijn et al. 2020, Mancini et al. 2020) and ecosystem services (Aizen et al. 2020, Mulder et al. 2017, Petit et al 2020, Vanbergen et al. 2020), and raised fears for environmental and human health (Kremen 2020, Opdam 2020).

In many places, the predominant form of agriculture is arable farming, where arable fields are the dominant land use. Much of current, environmentally-sensitive arable landscape policy deals with modifying structures and management at the field to regional scales, including direct reductions in pesticide use, increasing the diversity of plant cover, introducing semi-natural habitats and modifying the arrangement of intensive agriculture, such as ecological similarity or land sharing / land sparing (Brown et al. this issue, Grass et al. this issue). These managements have been shown to have benefits for society through the management of water pollution, the conservation of biodiversity (Kleijn et al. 2020; Skrimizea et al. 2020) and aesthetics (Schüpbach et al. 2020), for example, and for farmers through the delivery of ecosystem services such as pollination and pest control (Aizen et al. 2020, Bennett et al. this issue, Bihaly et al. 2020, Faichnie et al. this issue, Holland et al. 2020, Howlett et al. this issue, Petit et al. 2020, Vanbergen et al. 2020). Landscape management programmes are now well supported in national and international regulations and by agreement (European Environment Agency 2019, Haan et al. this issue, Opdam 2020), and in different countries are supported by payments and subsidies made to farmers who adopt these landscape management practices. We believe, however, that arguments for the design of future agricultural landscapes should be placed within the context both of our ongoing needs for farmland to provide food for humanity and of the mechanisms we have available to us to transform these spaces. Current approaches to modify agricultural landscapes suffer from two issues that need to be addressed. The first is that not all farmers see these landscape management practices for sustainability and biodiversity. The second is that many of these managements for building future landscapes do not consider climate change and so may not be fit for purpose if they are designed for environmental conditions that will no longer exist. Although implementation is complex, we believe that it is both necessary and possible to find mechanisms to build future biodiverse and sustainable landscapes that appropriately incorporate farmer needs and expertise and take account of climate change.

Climate change is an existential threat to farmers and current patterns of arable agriculture. As climate changes and become more variable, agricultural productivity will become less reliable and more prone to unpredictable failure (Chan et al. 2018, IPCC 2018). The performance of many of the crops that are currently highly productive will decline significantly (Morgounov et al. 2018, Tigchelaar et al. 2018, Vogel et al 2019) and the places where these crops can be grown will shift polewards (Ceglar et al. 2019, Ritchie et al. 2019, Zhang and Cai 2011). This has the potential to render arable farming unprofitable in parts of Europe within the next ten years (see European Environment Agency 2019) so farmers will be faced with a choice: either leave farming or modify their practices and the crops that are grown (see Ouin et al. this issue), adopting new cultivars or species able to be cultivated profitably under future climatic conditions. Yet, we believe that farmers will not adopt new crops or cultivars individually because they use crops within agronomically well-understood sequences, called rotations (Bohan et al. 2011b, Therond et al. 2017) for managing weeds (Weisberger et al 2019), pests

(Vasileiadis et al. 2011), diseases (Pankhurst and Lynch 2005) and soil quality (Bullock 1992). We expect, therefore, that farmers will modify their current rotations by swapping in new crop cultivars for old or by inserting new crops where these changes are economically, agronomically and culturally acceptable to them.

We know from past research that changes to rotations, and hence the diversity of crops, will lead to changes in biodiversity and the ecosystem services supported by farmland, both within a field and at landscape scales (Albizua et al. 2015, Bohan et al. 2011b, Tamburini et al. 2020). Agricultural rotations have changed over the last three hundred years, continually adapting to address local and national challenges and to the increase in the use of chemical inputs following the Green Revolution (Francis 2005). Currently, specific choices for particular crops, as a result of land tenures, national and international regulations (e.g., sugar beet quotas), or profitability of crops, modify these patterns. In the future, climate-derived crop choice and change to rotations will have the potential to markedly affect the future of agricultural landscapes (Storkey et al. 2019). A portfolio of acceptable future rotations, each of which is the result of farmer-relevant decision-making at farm and field scales, could drive the composition and the dynamics of future landscape mosaics. Dealing with such complexity is daunting, but it also highlights the new opportunities to influence the composition and configuration of agricultural landscapes.

It is here that a potential mechanism for designing future landscapes becomes apparent. Climate change will affect crop performance, leading to the requirement for changes in rotations that will affect future ecosystem services provided by agricultural landscapes. By using farmer knowledge of crop agronomy to propose future rotations, including novel cultivars or species of crops, in the light of climate change predictions, researchers could then model these proposed rotations to estimate likely effects on economy, biodiversity and ecosystem services. Results could be validated through empirical studies in regions where those rotations are already used. This is different from the predominant approach in climate change research that models the future performance of crops and their effects individually (Leng and Huang 2017, Leak et al. 2016, Sloat et al. 2020). Finally, researchers could work with farmers and other stakeholders to use this new information to select from the proposed rotations those that meet the needs of the farmers and provide benefits for society. This process of co-development would avoid wasted effort developing theoretical rotations that are not practicable or acceptable (Mgendi et al. 2019) and any on-farm empirical validation of the predicted economic and ecological effects could serve as a farmer-derived demonstration of future rotations.

Here, we report on a process to bring all these components together. As part of the *PREAR* project, we developed a co-development workflow to build future novel rotations that meet climate change and environmental criteria while being farmer acceptable (Section 2). This workflow was developed from questionnaire-led research on farmer attitudes to arable farming and climate change, which demonstrated the importance of considering rotations, not just crops (Section 3). We demonstrated the opportunity for using this workflow in targeted locations through an analysis of 11 million recent, commercial crop sequences from France, England and Denmark (Section 4) and development of a web-based tool that allows users to explore the effects of climate change on crop performance and allows farmers to construct future rotations (Section 5). Integrated analysis of the benefits of crops within rotations required us to predict the economic and ecological effects of rotations at field and landscapes scales (Section 6 and 7) and, as a demonstration, we conducted an empirical validation of the ecological modelling in field trials of specific rotational histories (Section 7). In this way, we work through the workflow as a ‘proof of concept’ that could be used by researchers and farmers and other stakeholders working together to co-develop novel rotations for European arable farming (Section 8) and thereby design future agricultural landscapes that are acceptable to farmers and meet society’s environmental needs (Section 9).

2 A workflow to co-develop and select agronomically acceptable rotations that meet climate and ecosystem services criteria

Our initial conception was to devise future rotations using academic climate change scenarios and modelling of crop economic performance and the changes to ecological functioning. As would typically be done in climate change research, we believed that by combining such academic modelling with some knowledge of farmer attitudes and decision-making for adaptation to the effects of climate change, it would be possible to propose future rotations that would meet criteria of agronomic, economic and ecological acceptability. However, the preliminary results of the farmer questionnaire (Section 3) very quickly disabused us of this notion. The questionnaire results showed that farmers had a keen interest in and a need to develop new rotations to adapt to climate change, but academic climate change scenarios, e.g. which present future climatic change as probabilities or frequencies of a given temperature or rainfall event, were not well adapted for farmer needs. This is because they are not expressed with regards to the daily weather experienced by the farmer, and they are often couched in terms of extreme climate events, lending a tone to the scenarios that farmers interpret as pessimistic. Both these outcomes meant that farmers appeared to be restricted, or self-limited when considering potential future rotations (Morton et al. 2011, Spence and Pidgeon 2010). Therefore, we concluded that it would be necessary to harness farmer sentiment and knowledge to co-develop rotations.

This can be visualised as a workflow (Figure 1) that could be run in target regions. Target landscapes could be selected based on the greatest opportunity to make changes from current cropping patterns (Section 4), and this data could also be used to identify landscapes already using those rotations that would be appropriate for validating the results of the workflow (e.g. Section 7). Of course, this could be scaled up to regions of Europe, or even the whole European Union, depending on the policy measures being considered.

[Figure 1 here]

The workflow starts with farmers and other stakeholders, such as agronomic advisors, coming together in focus groups to discuss climate change and their agronomic goals for their rotations, and to explore and discuss potential future rotations that meet these goals. This process is facilitated by a web-based software tool, the *Future Rotations Explorer* (https://shiny-apps.ceh.ac.uk/prear-future-rotations-explorer/; described in Section 5), which provides farmers with an overview of predicted yield changes or crops and user-selected rotations with future climate across Europe and be used to explore the performance of different rotations under future climates for specific landscape locations. Discussion in the focus groups would select a short-list of proposed rotations that could be subject to more detailed modelling of the economics (Section 6) and the ecology (Section 7), which can then be synthesised to indicate expected changes in ecosystem services. The evidence from this detailed modelling could be discussed with farmers in focus group settings to weigh the relative importance of the agronomic, economic and ecological performance of each proposed rotation (Section 8). From such evaluation the best rotations can be selected: those that are deemed to be acceptable to farmers and assure agro-ecosystem service provision and resilience to climate change.

3 Understanding farmer attitudes to rotations and adaptation to climate change is foundational to co-designing solutions

Farmers are agents of change in arable land so understanding their attitudes to cropping (i.e. the importance of rotations versus individual crops) and to climate change is the foundation to co-designing practical and effective solutions to the challenges such as climate change. To date, relatively little work has been done on farmer attitudes to using rotations to achieve cropping objectives or to their attitude to responding to climate change, despite some modelling studies considering these (Teixeira et al. 2018). In designing the workflow, it was necessary, therefore, to understand the way that farmers think, particularly in their decision-making for cropping (see Feola and Binder 2010, Feola et al. 2015, Wolf 2011) and so we developed a crop rotation questionnaire, to be run via face-to-face conversations (see Young et al. 2018). The questionnaire was co-designed with farmers to explore whether farmers use rotations and are interested in using them to mitigate climate change, and to explore their attitudes to climate change and adapting to its effects. The details of the questionnaire and the full results are described in Bane et al. (2020), so here we present a summary to describe how it informed the development of the workflow.

Construction of a farmer questionnaire

The process of co-designing the finalised questionnaire took 18 months and involved an iterative process of specification of the questions and interpretation with a small group of farmers to improve the questionnaire. The initial specification was developed with a network of eight farmers in the area around Dijon, Bourgogne-Franche-Comté (Bgn) in France. We specified to this initial group of farmers that we would like to understand better how farmers manage their cropping (whether as complete rotations or on an individual crop-by-crop basis), and the objectives they have and the constraints they face, particularly in relation to climate change. The processes of co-construction improved the questionnaire by defining when questions were open (with later classification of answers via coding) or closed (using yes/no answers or a Likert scale (Jamieson 2004)). During this co-development process, discussion with the farmers provided the range of possible answers that we used in choice questions about objectives and constraints for cropping. Objectives included ‘financial independence’ or ‘control over a pest’, while constraints were factors that limit the farmer’s ability to practice as they might, such as government regulation or biotic pressure.

The co-construction structured the questionnaire into three sections (Forster et al. 2020). The first collected information about the farmer, their farm business, land and farming practice, including the crops grown and their current standard rotation(s). The second section of the questionnaire covered the current situation faced by farmers, specifically asking whether farmers had already begun to make changes to their practices due to changing weather patterns, to their flexibility of practice and to their objectives and constraints for current cropping practice. Given our interest in whether farmer cropping practice is done as rotations or individual crops, the questions of objectives and constraints in cropping practice were posed twice, once with respect to using rotations and once for individual crops; simultaneous questioning would distinguish rotational versus crop-based planning by farmers (Feola et al. 2015).

The final section dealt with climate change and its consequences for cropping practice. This evolved considerably over the course of co-creation. In the initial discussions with farmers climate change was presented as an ‘academic’ scenario, which stated durations of change and the frequencies and variances of particular extreme weather events. We found that this did not work and that farmers do not use this form of academic language or concept. Rather, farmers are interested in weather, not future climate *per se*, and they tend to have a negative view of climate change, seeing it as a threat. Instead, we developed an approach to describe climate change in terms of farmer-relevant information and to overcome the potential for bias in the presentation we used two viewpoints of the same scenario: one was optimistic, the other was pessimistic (Table 1). We asked farmers how they might change their cropping practice and whether they would modify their rotations in response to

the contrasted optimistic/pessimistic viewpoints might also allow us to determine the sensitivities of farmers to particular presentations of climate change.
[Table 1]

Study Regions and Farmer networks

We applied this questionnaire in four distinct regions (three in France and one in the UK) that formed an approximately North to South latitudinal gradient (Figure 2). We expected that the current impacts of climate change would be more negative and more severe further south along the gradient (European Environment Agency, 2019; Blöschl et al. 2019). The questionnaire was translated from French to English, with minor changes to adapt it for the UK farming situation (Forster et al. 2020).
[Figure 2 here]
The questionnaires were completed through semi-structured interviews conducted by one of the authors in four regions (Figure 2). They were conducted in three regions across France in 2018 (13 farmers in Occitanie in the south-west, 22 farmers in the Bourgogne-Franche-Comté in the central-east and 12 farmers in the Hauts-de-France in the north) and 28 in southern UK in 2019. Farmers were recruited via contact through professional networks (fully described in Bane et al. 2020). Therefore, the farmers were not selected to be 'representative', but the questionnaires provided a method to understand a range of motivations and responses to help us understand what to consider when co-designing resilient future rotations. This approach enabled us to gain a deeper understanding of the range of factors influencing the decision-making of this sample of farmers. We believe that this is likely to be indicative of the motivations of arable farmers, at least in France and the south of the UK, and possibly more widely, and it provides the basis for future, larger studies of farmers.

Do farmers manage using rotations?

The responses to the questionnaire demonstrated that farmers were extremely interested by climate change and its effects on their farming objectives and practices. Most farmers (88%; varying across regions from 73% in Bourgogne-Franche-Comté to 100% in the UK) stated that they achieved their farming objectives using crop rotations, and most responded similarly to the questions about objectives and constraints of individual crops versus rotations (Bane et al. 2020). This indicated that while individual crops contribute to the achievement of farming objectives, they do this as part of coherent crop rotations.
We found that financial and soil quality objectives, achievable through rotations, tended to be paramount in the responses of farmers with questions of the reduction and distribution of working time being of lowest importance amongst the objectives offered (Table 2). Objectives of individual financial, livestock feed and infrastructure autonomy were somewhere in between. Reordering the responses in all localities by the order of the importance of objectives and constraints found in the UK produced remarkably similar patterns between the regions (Table 2). This might suggest that there is a generic conception or understanding of cropping objectives and constraints, what can be achieved via rotations, and of their relative importance, across all farmers in the regions of the study.
[Table 2 here]

Rotations and climate change

We found that farmers varied in their response to the predicted impacts of climate change (Table 3; Bane et al. 2020). Most farmers would diversify or lengthen their rotations, which indicates the potential for agronomically acceptable future rotations to align with the political agenda to diversify agriculture for the benefit of wildlife and ecosystem services. A small minority of farmers would shorten (and simplify) their rotations in response to the effects of climate change. However, it was also striking that the presentation of climate change impacts had profound differences on the responses of farmers. When presented with the pessimistic viewpoint (which emphasised the challenges that climate change will bring), farmers were less likely to diversify or lengthen their rotations, but more likely to shorten their rotations.

[Table 3 here]

These results show an effect of sentiment or outlook on the choice of rotation. There are at least two important consequences of this result. Firstly, it suggests that presenting both optimistic and pessimistic scenarios might lead to a greater range of possible responses being considered, with greater flexibility and acceptability of rotational response to climate change. Secondly, it suggests the hypothesis that farmers that have either optimistic or pessimistic outlooks might be differentially disposed to adopting rotational change in response to their perception of future climate.

[Figure 3 here]

This expectation of sentiment-dependent adoption becomes extremely important given the final result of the questionnaire. When we asked whether the farmers considered themselves optimistic or pessimistic about climate change, a clear pattern in the responses was that they became progressively more pessimistic the further south along the transect (Figure 3; Bane et al. 2020). Given that farmers towards the south of the transect had a higher likelihood of having experienced climate change, this result suggested that previous exposure to climate change related issues were more likely to render a farmer pessimistic about the future and, when coupled with previous results, it suggests a hypothesis that farmers might become less flexible in the rotational responses that they might employ following exposure to climate change.

Developing future rotations with farmers

The questionnaire results provided some key messages for the development of farmer-acceptable rotational approaches to combat climate change effects on ecosystem services. The first is that the farmers questioned thought in terms of rotations to achieve their cropping goals and were keen to develop rotationally-based solutions to mitigate climate change. Our work suggests that this can be supported by a move away from thinking about climate change in terms of academic projections of climate. ‘Academic’ scenarios of climate change are not adequate for communicating with farmers. Instead, we used descriptions that explicitly describe optimistic and pessimistic viewpoints to elicit a fuller range of possible responses. Knowing the range of possible responses helps decision-makers to understand the interventions that might be required to support farmers in making these changes. Together, these could enlarge the range of possible rotational responses being considered and confront, directly, some of the problems of adoption and mitigation that are linked to strictly pessimistic farmer outlooks and sentiment that limit flexibility (see Morton et al. 2011, Spence and Pidgeon 2010). The questionnaire demonstrated that farmers are generally willing to change their rotations to adapt to climate change and to co-develop future scenarios of rotational usage patterns that are based upon good climate science and farmer agronomic knowledge. We believe this work supports and advocates for a novel approach to constructing climate-rotation scenarios that couples the agronomic knowledge that farmers have and their farming objectives to scientific understanding of weather orientated scenarios of climate change and predictions of future economic and ecosystem service outcomes. Such co-development, via the workflow presented in Section 2, could produce future crop rotations that are explicitly farmer-acceptable and assure ecosystem service provision in the face of climate change.

4 National patterns of rotation

When working at the landscape level, agroecologists typically focus on patterns and metrics that describe crop diversity and configuration in a single year (Wilson et al. 2017), treating them as static drivers of biodiversity and ecosystem services (e.g. Trichard et al. 2013, Fahrig et al. 2015, Marrec et al. 2017). The crop mosaic, however, is changing each year along the sequence of crops grown in rotation and in the longer-term through shifts associated with rotational intensification (*e.g.*, Robinson and Sutherland 2002). The simplification of the landscape to a static layer overlooks the complexity of these dynamics that are a key feature of arable landscapes (Arambu Merlos and Hijmans 2020).

Crop rotations vary in space and time, with regions existing on a continuum from monocultures or simplified rotations with break crops (such as years of wheat followed by oilseed rape), to more diverse and longer rotations designed to meet particular agronomic goals (Barbieri et al. 2017). Such changes in rotation patterns are likely to affect biodiversity and ecosystem services (Schellhorn et al. 2015, Vialatte et al. 2019), via their effect on the distribution and availability of food resources (e.g. seed and mass flowering crops) and provision of refugia across the landscape (Haan et al. 2020). These effects will not only impact biodiversity within arable fields but also spillover to impact species distributions and dynamics in adjacent habitats (Leenhardt et al. 2010, Melander et al. 2013, Mahaut et al. 2019). To date, the spatiotemporal organisation and the dynamics of arable crops in landscapes has largely been overlooked by agroecologists, and its description remains a significant methodological challenge (but see Rizzo et al. 2019).

There are at least four reasons why it is valuable to analyse patterns of crops at large scales. Firstly, current and past patterns of crops can inform us about the relationships between rotation and landscape diversity in space and time. Secondly, analysis of emergent patterns can reveal landscapes where there are opportunities to modify rotational management by developing new rotations that have the spatial and temporal patterning to shape and enhance the sustainability of these arable landscapes. Thirdly, this would identify regions where particular rotations are currently grown that might serve as landscapes for demonstration and validation of rotational predictions. Fourthly, the analysis of current patterns will also highlight outlier landscapes that depart from any relationship between rotational diversity and landscape diversity, revealing crop concentrations, high spatial synchrony or low temporal diversity. These landscapes might be prioritised as places of opportunity for intervention and study, in which the workflow depicted in Figure 1 could be used to develop future-proof, ecologically and economically sustainable rotations. In this section, we outline an analysis and metrics to characterise and contrast crop diversity, in space and time, for different arable landscapes and how these contribute to the crop mosaic of agricultural landscapes in three European countries.

Methodology

Field-scale crop data

We describe the diversity of crops, and their organisation in time and space, for arable landscapes monitored across three countries: England, France and Denmark. These time-series are for the cropping history of 1,629,429 fields in England, 9,186,074 fields in France and 578,801 fields in Denmark. For England, we used two data sets to build the crop sequence for 1,629,429 fields over a 4-year period between 2015 and 2018. The standardized collection of data for English fields and crops began in 2015. This systematic reporting allowed the production of a detailed crop map that combined data from the Land Parcel Identification System (LPIS) and the Basic Payment Scheme (BPS) database. The BPS data contains personal and sensitive information and is therefore not readily accessible and

requires specific agreements. Thus, we only used this product for the year 2015 when no other data source was available. For 2016 to 2018, data from the UK Centre for Ecology and Hydrology (UKCEH) Land Cover Map *plus: Crops* (https://www.ceh.ac.uk/crops2015) was used. This is derived from openly available remote sensing data (Sentinel-2 optical data) that is validated against data from the Rural Payments Agency (87% accuracy in 2016 based on 860,000 fields across nearly one million hectares). The UKCEH crop map classifies the crop grown in each field larger than two ha and subdivides cropping units where more than one crop is detected. For our analysis, we aligned the classification of the two data sources by reassigning the 119 crops reported in the BPS in 2015 to the eight predominant crop classes (seven arable crops and improved grassland) reported in the CEH Land Cover Map. All crops in the BPS not specified in the CEH Land Cover Map were classified as belonging to the category "other". In France, we had access to a dataset, derived from the French LPIS, describing crop sequences across nine years (2006-2014). Algorithms and predefined rules to identify and link the annual LPIS data to derive this dataset are presented in Levavasseur et al. (2016). This dataset covers almost all arable fields in France (99% of the estimated arable cropland in 2009), providing access to the crop sequences reported in 9,186,074 distinct land parcels. Because the composition of crop sequences varies substantially along the environmental gradient sampled across France, we stratified the data set into three regions: North, Central-South-West and East. This stratification allows for a better representation of the dominant crops grown in each region, within a limited number of classes. For each of the three regions, we classified the crops reported in the LPIS into the eight dominant crops (seven arable crops and improved grassland), and one additional class for all other, less abundant crops. To avoid sequences with missing years, we excluded all the fields that had one or more unknown crops along the 9-year sequence. This resulted in the removal of five of the 96 departments of Metropolitan France (Alpes-Maritime, Isère, Jura, Haute-Corse and Corse-du-Sud). In Denmark, we used data gathered from 578,801 fields over eight years (2010-2017). The crop sequences were extracted from field parcel maps curated in the Danish General Agricultural (Landbrug) Register database of the Miljø-og Fødevareministeriet (Danish Ministry of Environment and Food). As we did for France and England, the 21 crop codes used in the Danish data were classified into eight dominant crops (seven arable crops, improved grassland) and a category defined as 'other'.
Given that the classification available in France did not distinguish between winter and spring-sown crops, we aggregated winter and spring-sown categories for wheat and barley for England and Denmark. Across the three countries, a total of twelve dominant categories were represented (Table 4). The standardized pool size allows us to provide a fair comparison of crop diversity across landscapes, regions and countries. Nevertheless, because our data covered only four years in England, eight in Denmark and nine in France, we restricted the French data to the eight most recent years (2007-2014) and used hypergeometric sampling to extrapolate the expected crop diversity in eight years of rotation from the four years of rotation available in England (Hurlbert 1971, see below). We used the centroid of each field or crop unit to assign it uniquely to a 5 x 5 km grid cell. Our focus was on crop rotation in arable fields and therefore excluded any fields recorded as permanent grassland, but we retained fields with crop sequences that included both grassland and arable crops. All fields categorized as perennial crops, including orchards, vineyards, agro-forestry and semi-natural grasslands were also excluded.

[Table 4 here]

A conceptual framework to describe spatial and temporal arable crop diversity

A multitude of metrics and approaches to evaluating species diversity have been proposed and used in ecology (Hurlbert 1971, Colwell et al. 2004, Jost 2007, Chao and Jost 2012, Crist and Veech 2016, Gaggiotti et al., 2018), and for describing crop diversity in time and space (Arambu Merlos and Hijmans

2020). Amongst these, rarefaction curves can be derived from a unified statistical framework and provide a rigorous analytical basis to describe and contrast diversity over time and space (Chao and Jost 2015, Crist and Veech 2016, Chase et al. 2018). These curves encapsulate the multivariate nature of diversity and can be used for consistent comparison of diversity across regions, scales and treatments. Here we build upon the concept of individual-based rarefaction (IBR) curves, defining each field in a given year as an individual event with a single value of the crop identity. From this abstraction, we derived rarefaction curves that depict different dimensions along which crop diversity can shape arable landscapes (Figure 4). Specifically, we derived IBR curves from samples accumulated in different ways: i) in space, to represent the diversity expected within a given year across arable fields in a region; ii) in time, to represent the diversity expected over *n* years in a single field; and, iii) in space and time, to represent the entire expected diversity (Figure 4). This approach facilitates the assessment of crop diversity in arable farmland, providing valuable insight into its structure in space and how the observed crop rotation influences this in time.

[Figure 4 here]

Evaluating diversity in space and diversity in time

We expected crop richness would increase with the number of fields (cropping events) sampled (Figure 5), but we would also expect the shape of this curve to be determined by the abundance distribution (dominance and rarity) and the spatiotemporal structure (over- and under-dispersion) of crops in the landscape. These drivers can readily be compared (see McGlinn et al. 2018 for species diversity examples) for crops sampled from the entire landscape or from fields sampled across a specific dimension (time and space). Although these accumulation curves can be built empirically, the probability theory of the hypergeometric distribution offers the possibility of extrapolating the diversity metrics in space and time (Hurlbert 1971), with acceptable precision so long as this is limited to sizes less than twice the observed sample size (Chao and Jost 2012). When contrasting extrapolated diversity estimates (e.g. 8-year estimate from 4-year sequences) with the estimates obtained from the full sequence (8-year estimate from 8-year sequences), extrapolated indices tend to underestimate the observed diversity and result should be interpreted accordingly. Here we extrapolated diversity metrics along the IBR curves so that the four-year crop sequence for England was extended to a sample of eight years to match the series available for France and Denmark. For each 5 x 5 km grid cell, we computed three IBR curves from crop sequences sampled along time (within fields), space (within years) and from the entire landscape (across time and space) and derived five metrics based on the crop diversity in time, in space, in both time and space, and the ratios of these (Table 5a). All IBR asymptotic accumulation curves were derived analytically, using the rarefaction function implemented in the R package mobr v2.0.0 (McGlinn et al. 2020).

[Figure 5 here] [Table 5 here]

Conceptually, our method considers all the fields within a 5 × 5 km rectangular landscape where arable crops are part of the four- or eight-year crop sequence. To calculate a single S_8 *space*, we computed the IBR curve for each year and averaged, over the years, the number of crops expected from a sample of eight (n = 8) fields in a given year. The same procedure was applied over time in fields, computing S_8 *Time* as the average, across all fields, number of crops expected from a sample of eight (n = 8) years in a given field. In contrast to S_8 *Time* and *Space*, S_8 *Landscape* is derived as the number of crops expected from a sample of field-year combinations from across both the space and time dimensions.

These metrics provide an assessment of the crop diversity (in time, in space or in both) but do not provide information on how the crops are structured. To investigate how crop diversity is structured, i.e. information about the importance of rotations, we computed the Beta (β) diversity for the two dimensions, βS_8 *Space* and βS_8 *Time* (Table 5). These provide insight into the temporal and spatial distribution of crops, relative to the abundance distribution observed in the entire pool of crops grown in the 5×5 km landscape across the whole time. This serves to highlight landscapes where crops are abnormally concentrated in one dimension or the other, indicating the departure of particular landscapes from the overall relationship between crop (rotational) diversity in time and diversity in space (landscape) that might merit interventions to modify the current rotational pattern or landscape management. Conceptually, therefore, the βS_8 *Time* indicates the opportunity within a given landscape to increase crop diversity along the crop sequence, and thereby move the time IBR curve toward the level of the landscape IBR curve (see Figure 4 and 5).

Temporal and spatial diversity of arable crops

The average number of crops expected to be grown in a field over eight years varies markedly across landscapes, with extremely low crop diversity in some regions of France, most likely associated with intensive monocultures (Figure 6a, c; 7a, c; 8a, c). Nonetheless, the range of the expected number of crops is broadly similar between the three countries, with the mode of the expected crop richness ranging from 3 to 3.7, across eight fields or years. In some parts of southern France, modal values are systematically lower, with less than two crops over the eight years of rotation. There was a strong relationship between the spatial diversity of crops (S_8 *Space*) and the temporal diversity of crops (S_8 *Time*), as shown in panel c of Figures 6-8, suggesting that crop diversity observed across fields in a single year are representative of the diversity of crops in rotation in the landscape. Our results suggest that this is particularly true in France, where a wide range of diversity is observed across the different landscapes, showing some landscapes with very low diversity (left tail in Figure 7c). Although this relationship is positive in all three countries, it is relatively weak in Denmark, partly because there is less variation in the diversity of crops in the rotations observed between the different landscapes. The richness of crops expected from samples aggregated over space, however, is very similar to what was observed in England and much of France.

[Figure 6 – 8 here]

When we consider how crop diversity is distributed across time and space (Figure 6b, d; 7b, d; 8b, d), it is possible to identify regions with substantially lower crop diversity along the temporal dimension relative to the diversity grown across the landscape (i.e. Cheshire in England, South West in France and West Midtjylland, Denmark). The beta diversity metrics provide information on the opportunity for changing rotations to increase spatio-temporal diversity. The opportunity metric (βS_8 *Time*) suggests that the diversity of crops used in rotations grown in those landscapes can be increased with crops that are already grown in that landscape. Only a few landscapes were characterised by opportunity scores indicative of synchrony of crop rotations (βS_8 *Time* < 1, Table 5b). These landscapes could reflect farmers' behaviour whereby the fields in the landscape tend to be at the same point in the crop rotation, irrespective of whether the rotations are simple or diverse. Spatial standardisation, where βS_8 *Space* > 1, could be de-synchronised to allow some of the diversity of cropping that exists in the rotation to translate into spatial diversity. Locations with lower temporal diversity (S_8 *Time* = low) also tend to have higher opportunity scores (βS_8 *Time* > 1), indicating landscapes of "depauperate rotations". These landscapes have an overall greater likelihood of simple rotations and these appear to be linked to particular crops. Low levels of temporal diversity in France, as an example, appear to be associated with high proportions of maize in the rotation.

With this analysis, IBR-derived metrics can be used to understand how crop diversity is distributed in space and time, and also to identify landscapes of opportunity. It is important to state, however, that these metrics only consider the arable part of the landscape and do not evaluate those non-arable habitats that contribute significantly to the sustainability of agricultural landscapes. It also does not take into account crop identity, which may be associated with a deeper agronomic understanding of the composition of the cropping sequence and agronomic benefit for weed control, integrated pest management and soil fertility (Barbieri et al. 2017). Future improvements in data availability, crop descriptions, possibly via advances in artificial intelligence for the identification of crops from satellite images that are being incorporated into Copernicus (https://www.copernicus.eu/en), and alternative methods of considering rotations (Levavasseur et al. 2016, Stein and Steinmann 2018) may solve many of these problems. It would be straightforward to adapt the current analysis and opportunity metrics to consider other aspects of diversity, such as the functional diversity of crops grown across space and time. This would be particularly useful for quantifying the distribution and availability of resources and refuges in arable landscapes or for highlighting areas with intensive but infrequent disturbance.

This analysis dissected the spatial and temporal component of crop diversity and showed how rotation can contribute to crop diversity at the landscape scale. We can use these derived opportunity scores to identify landscapes with diversities that are below their potential. These landscapes might be considered as priority sites of future work and intervention where co-development, using the proposed workflow, might allow farmers to postulate agronomically acceptable rotations, and also select those that are resilient in the face of climate change. Modelling of these rotations would also help envision what future national landscape diversity might look like.

5 A method for co-developing new rotational scenarios – The Future rotations explorer

Current national patterns of cropping, as explored in Section 4, are at least in part linked to farmer sentiment and decision making for rotations, as considered in Section 3. Future changes in rotation will be determined by the flexibility of farmers in considering and adopting new rotations as the effects of climate change mount, and indeed as they already experienced in the South of Europe (European Environment Agency 2019). The questionnaire suggested that those farmers who have had the most exposure to climate change showed increasing pessimism about its effects and inflexibility for the adoption of new rotations. If this were to be the case, then it becomes possible that without help to conceive new rotations farmers would be locked into their current practices, leading to existential problems for the continuation of farming in Europe as crop yield and performance decline. As a mechanism to avoid this, a web-based tool, the *PREAR Future Rotations Explorer* (*FRE* https://shiny-apps.ceh.ac.uk/prear-future-rotations-explorer/, Figure 9 and 10), was conceived to help farmers explore the consequences of climate change for their crops and rotations, and to conceive new rotations that might mitigate any real or perceived future loss of performance.

It was important that the *FRE* could be used by farmers, and other stakeholders, without delving too deeply into the detail of academic climate change scenarios that farmers do not find useful. The tool is, however, based upon academic climate change scenarios and so facilitates a dialogue between farmers and scientists around questions of climate change and rotations. The tool is designed to work on a web browser, over the internet, and to be used in farmer focus groups. It presents information in both French and English and could readily be modified to other languages. Initially, a map of Europe is presented to farmers and stakeholders (Figure 9), displaying the % change in yield of a crop, from the predicted yield in 2010s to a particular date in the future. Farmers can select one of the nine most commonly sown crops in Europe, modelled on 12 x 12 km grid squares.

[Figure 9 here]

These predictions of crop yield change were made using the *WOFOST* crop model (de Wit et al. 2019). Arable land was identified in 250 x 250m grid cells from Corine land cover data. The Lapse rate methodology (Robinson et al. 2017) and a digital elevation model (EU-DEM v1.1) were used to downscale climate variables of maximum and minimum temperature, precipitation, wind speed, vapour pressure and solar radiation from the 12 x 12km grid of the UKCP18 climate predictions for Europe. These were averaged for each 12 x 12km grid square and, with the dominant soil texture class from the European Soil Database v2, were used to predict water-limited potential crop yield in Rwofost 0.2-5 R package, using the 'weight of storage organs' as the yield for each crop. For each grid cell and each crop, we calculated the change in yield from the 2010s to each year in the 2030s and 2050s and took their average to give the predicted change in yield.

Users can select one of two time periods (2030s and 2050s) to consider future climate change effects on crop yield. While these time periods are based upon the UKCP18 academic scenarios, this map-based exploration facilitates discussion of climate change by concentrating on effects that have direct importance to farmers – change in crop yield. In a second step, Farmers can use the *FRE* to consider rotational effects of yield change for any specified location by selecting the "Rotations Explorer" tab. On selecting a particular 12 x 12 km locale, such as the one near Dijon, France represented by the blue box in Figure 10, the farmer can enter his current rotation; for instance, a rotation of wheat, winter oilseed rape and spring barley that is commonly used around Dijon, France. For each crop there is a forecast % change in crop yield and the average change represented by the orange line on the bar graph. This information can then be stored for future discussion by pressing the tab "Add to compare". For the particular case of Dijon, France there is a forecast 12.4% decline in yield across the standard rotation by the 2050s. We have found that such a decline is likely to surprise the farmer and leads to discussion about how rotations can be modified. In the *FRE* farmers can explore alternative rotations through lengthening or shortening their duration and/or changing the crops in an attempt to mitigate the predicted loss. For example, substituting rye for winter oilseed rape would reduce yield loss in Dijon to under 7% but may not be agronomically acceptable. Lengthening the rotation by introducing rye and field beans would reduce yield loss to 6% over a longer period but is agronomically acceptable. Rotations that farmers deem acceptable can then be saved for a later focus group discussion to select 'stakeholder-acceptable' crop rotations.

[Figure 10 here]

It should be made clear to all users during discussion that there are limitations to the *FRE* tool, especially based on the limitations of crop modelling. For example, all models have their limitations and the *WOFOST* model validation indicates that the predicted yield change of some of the crops may be more reliable than for others (de Wit et al. 2019). Change in yield is mapped for only those grid squares with arable land present in the 2010s and the presence of a prediction does not mean that the yield of a crop is sufficient for it to be profitably grown in the grid square either now or in the future. The crop models do not consider the potential for crop cultivars or agronomic practices to change in the future: no attempt was made to include new or modified practices such as intercropping and irrigation, and no allowance was made for climate change adaptation via the development of tolerant crop cultivars. This was partly an explicit choice because we felt it was better to adopt a common, simple framework of predicting % yield change in conventional crops. This allows the farmer to use their agronomic expertise and understanding of the industry to decide whether the forecast changes in yield were important enough to consider a rotational change, in the light of future developments of management and cultivars. In essence we allowed the farmers to use the % yield change both as a metric of future crop performance and an indicator of how much work it was necessary for the industry to do to maintain that crop and rotation in the locality in the future.

This tool-based method for co-development allows us to bring together a number of key elements of understanding, such as for farmer sentiment and need from the questionnaire (Section 3), opportunity scores to identify landscapes where rotational change might be necessary (Section 4), and the need to co-develop future rotations that are agronomically acceptable to farmers by maximising their input from the very start of the process. The benefits of this are great. Using maps of the rotational opportunity across Europe, it would be possible to identify landscapes where focus groups could be run with local farmers, guided by the *FRE* tool. Farmers would be educated to the likely yield effects of future climate on their rotations, whilst avoiding diving too deeply into academic climate scenarios. We could then use their agronomic knowledge and scepticism to choose future scenarios that meet simple criteria of yield change but are in principle agronomically acceptable. Subsequent discussion and debate between the farmers in the focus groups would then select a suite of rotations that would form a co-developed scenario of potential rotations for each identified landscape. These co-developed, rotational scenarios would then form the basis of the socio-economic (Section 6) and natural science (Section 7) modelling for the assessment of ecosystem service change.

6 Economic factors of changing crop rotations in arable farming

The scenarios of future rotation constructed by farmers identify the rotations that are agronomically acceptable and resilient to predicted future climates (Section 5). However, the true consequences of such novel rotations are unknown beyond simple predictions of yield response to climate change derived from the *WOFOST* models. In the *FRE*, the yield changes that farmers can use to devise new rotations are simple aggregations of the yield changes and we assumed no interaction in the yields between the crops in the rotations. In reality, yield and profitability could be affected in multiple ways. Firstly, changing the proportion of land share of the crop types grown, due to modifying rotations, will cause knock-on effects on the wider agricultural industry that could affect the profitability of different crops (Duru et al. 2015b, b). Secondly, there are spillover effects from one year to the next: for instance, the profitability of wheat may vary whether it has been grown after winter-sown wheat or spring-sown oilseed rape, due to the different cultivation and tillage affecting weeds, pests and disease in different ways, and hence affecting the use of costly fertilisers and pesticides. Finally, yield could be affected by climate change. For farmers, the consequent economic effects will be important for their choices of rotations, rendering some agronomically acceptable rotations economically undesirable. Here we detail how economic modelling can be applied to explore rotational change, and how it could be used within the workflow.

It is important to note that the example rotations that are modelled in this section are not those co-developed with farmers. Relying partly on observed data on crop choices used in section 4, we analyse the predominant rotations in Europe: winter wheat, spring barley and winter oilseed rape (Canola / Colza). We construct both ecological-economic models of stylised rotational systems and economic choice models based on observed rotations in real farming systems. The economic modelling focuses on the impacts on yield of climatic drivers and farmers' choices of crops in rotational systems. This represents the farmer as a price-taker, with no market power to influence the price of crops, and we do not attempt to model the agricultural market responses to climate and rotation changes. The interpretation of the outcomes of the models thus adds to the agronomical and ecological interpretations of rotational change in the workflow.

Rotationally driven crop yield under changing climate

Crop rotations have direct effects on farm returns because they are explicitly linked to crop choice; and crop choice is largely driven by expected prices and yields. The choice of crops sown in rotation is linked to agronomic and ecological factors such as soil fertility and weed control (Fuhrer 2003, Jones and Thornton 2003). Ecological factors in turn have direct impact on productivity and on agricultural inputs, including pesticide use. It is this combination of higher yield and lower input costs that drives the choices of farmers for rotations rather than continuous cropping (Hennessey 2006) and may be expected to trigger rapid and wide-scale change in crop rotational practice with climate change. Adaptation to climate change may begin with modifications of crop rotations via changes to the timing of cultivation and adoption of new crops and/or cultivars (Asseng et al. 2013). However, there have been few studies that examine this process in economic terms by modelling the effects on crop yield of rotation and climate drivers.

Here, we use field-level data on crop history from Denmark to assess the effect of rotation on crop yield, while taking the effect of climate into account. Our analysis uses an unbalanced panel of Danish farms from 2010 to 2016. The yield data is obtained from the National Statistics of Denmark. The crop history data comes from field parcel maps in the Danish General Agricultural (Landbrug) Register database of the Miljø-og Fødevareministeriet (Danish Ministry of Environment and Food). Seasonal weather variables were extracted from the Advanced Weather Research and Forecasting Model (Skamarock et al. 2008) at a 1 x 1 km grid scale for the whole of Denmark, except for the island of Bornholm.

We calculated the 'area share' of the current crop with respect to crops in the previous year. Our analysis focusses on the current crops of winter wheat, spring barley and winter oilseed rape, which together make up the greatest production volume and area cultivated in Denmark. The total number of observations (i.e. field-year combinations) used in our analysis are 10545, 11530, and 5903 for winter wheat, spring barley, and winter oilseed rape, respectively. The mean (Mean) and standard deviation (SD) of the variables for the three crops are given in Table 6. The 'area share' indicates the recent rotational history; for instance, for winter wheat fields, the wheat and barley shares were 0.43 and 0.18, respectively, indicating that, on average over 2011 to 2016, 43% percent of the current winter wheat fields were sown with wheat (winter and spring) in the previous year, and 18% were sown with barley (winter and spring).

[Table 6 here]

Data on crop yield is available per farm not per field, so all subsequent analysis was at the farm-level. We calculated the 'area share' of the current crop with respect to crops in the previous year and estimated the effect of area share on yield of the current crop. To simplify the analysis, fields of winter and spring crops of the same crop are grouped together for constructing the shares. Then, we use the share variables to ask whether changes in crop shares, across a rotation, leads to changes in realized yield. While climate and weather variables will drive crop choice, and in turn rotational shares, however here we focus on modelling the yield effects of the rotation share, controlling for weather in each growing season.

Modelling rotationally driven crop yield

We use a panel data fixed-effects regression to estimate parameters of yield for different combinations of crops and weather. We assume that yield is a function of crop history and other variables, including the weather. We model average yield per hectare, y_{it}, of farm i in year t as a function of crop history and weather variables, such that:

$$y_{it} = \alpha_i + \beta S_t + \sum_j \theta_j f_j(X_{jit}) + \gamma_t + \epsilon_{it}$$

where α_i is a farm fixed effect, γ_t is a year fixed effect, S_t are the farm-level area share variables of the current crop, X_{jit} is weather variable j for farm i in year t while $_{it}$ denotes the error term. Unobserved farm level time-invariant factors affecting average yield are accounted for using the farm fixed effect, α_i, while γ_t estimates sudden, discrete changes in average yield due to temporal shocks that are common to all farms. The weather variable, X_{jit}, includes average temperature and precipitation for the four seasons of Autumn, Winter, Spring and Summer. The growing period for winter crops in Denmark is September/October through to August, while for spring sown crops it is February/March through to August. We therefore analyse weather variables for the four seasons, in the cases of winter wheat and winter oilseed rape, while two seasons are analysed for spring barley. The weather variables are modelled with linear and quadratic terms to account for non-linearities demonstrated in previous studies (e.g., Mendelsohn et al., 1994; Schlenker and Roberts, 2009). All regressions are weighted by average crop area of the farm across years to minimize heteroskedasticity and to make the results more representative of the average growing area. The regressions include both farm and year fixed effects, implying that any estimates rely on farm specific deviation about the farm average after adjusting for shocks common to all farms.

Estimated crop yield effects of rotation

Table 7 presents the regression results for the three crops, controlled for variations in weather. For simplicity, the specific results for weather variables are not reported in Table 7, but they indicate that: (1) average yield per hectare is affected by both temperature and precipitation; (2) the effect of the weather variables varies by seasons and crop type; and, (3) the relationship of weather to yield is non-linear, as has been previously demonstrated in the literature (e.g., Mendelsohn et al., 1994; Schlenker and Roberts, 2009).

[Table 7 here]

The coefficients of the crop share variables indicate the effect that the crop share has on the yield of the current crop. This shows that with an increasing share of the same crop (as would be seen with repeated cropping), winter wheat and spring barley yields decrease. As the wheat share of winter wheat increases from zero to one (i.e. all wheat is grown on fields that grew wheat the previous year, as would occur with repeatedly cropping with wheat) winter wheat average yield per hectare decreases by 425 kilograms per hectare, while repeated barley cropping decreases average spring barley yields per hectare by approximately 286 kilograms. Increasing the barley share would also come with a cost to winter wheat yield of 363 kilograms per hectare. An increase in rotational shares of wheat, barley, and grass have a statistically significant positive effect on the realized yield of winter oilseed rape. Unexpectedly, an increase in rotational share of grass has a negative effect on the average yield of spring barley while it is statistically insignificant for winter wheat. The grass share therefore has different effects on spring barley and winter oilseed rape yields. Since we grouped all types of grasses (forage) into the "Grass" category, it is not clear what the mechanism behind these effects might be. The effect of the rotational share of oilseed rape, corn, oat, rye, and triticale on the average yield of the three crops are not statistically significant. However, this is not surprising given the negligible share of these crops in the data set. The only exception is the winter wheat area following oilseed rape which represent 26 percent of the wheat fields (Table 6).

The findings indicate that repeated cereal (wheat and barley) cropping results in a significant average yield loss. This result has the important implication that diversifying cereal rotations (e.g. in response to predicted effects of climate change) by including non-cereals could avoid yield losses from continuous cropping. In general, what these findings demonstrate is that changes to rotations have impacts on yields and that these can be estimated based on existing field data. For a given agronomically acceptable rotation, co-developed with farmers, the interactive economic impact on increasing the share of a particular crop in the rotation on a focal crop, such as winter wheat, can be calculated and communicated to farmers. In focus groups, these evaluations can then be discussed as part of a determination for whether any given rotation is economically viable.

Landscape spatial and temporal structuring of rotations

One of the reasons why there might be temporal spillover effects on yield is due to weed pressures. To explore this, we now move to a more conceptualised representation of rotations in arable systems. We represent the arable rotation system by two crops; wheat and oilseed rape. Growing wheat is, all other things being equal, more profitable than growing oilseed rape in most years. As was shown in the previous example, growing wheat after wheat comes with negative impacts on yield, compared with growing after other crops. In dicotyledon crops, like oilseed rape, broadleaved weeds tend to do well, and grass weeds do well in monocotyledon crops such as wheat. This is due to similarities in the biologies of the weeds and the crop which mean that monocot herbicides against grass weeds are less used in monocot crops for fear of damaging the crop, and vice versa. Rotations could therefore follow relatively simple, fixed patterns, such as alternating wheat and oilseed rape in consecutive years or by using two wheat crops, consecutively, followed by an oilseed rape.

Across landscapes, rotations might be run synchronously in the different fields. Such patterns would probably reduce time and overheads of management and organisation, because they are simple. However, there are likely to be trade-offs between management efficiency and the potential yield that could be achieved in an optimal sequence across space and time. Weed seeds disperse between years (and crops) by remaining dormant (Mahé et al. 2020) and may be dispersed to other fields by wind or agricultural machinery (Benvenuti, 2007), creating ecological interactions between fields that may impact the profits of the farmers of those adjacent fields. These effects are typically treated as externalities in economics. As a result, simple rotations that are optimised for weed control at the field level may not maximise resilience to weed at the landscape scale over time. Such ecologically driven externalities might make the coordinated choices of crops in rotation beneficial and consequently the optimisation of rotations should also consider the spatial dimension (Cong et al., 2014). Here we create a simple model to understand these principles and ask: i) is there an optimized rotation pattern for single fields that is superior to simple, fixed and repeated sowing of two crops (Simple rotations) in terms of farm resilience and long-term profit; and, ii) do asynchronous rotations outperform synchronous rotations for weed control and economic profit? These models are necessarily simple, but the results presented here provide an illustration of the way this could be modelled in real landscapes.

Describing model landscapes

We developed two optimization models (OMs) to identify optimal rotation patterns in different landscapes for maximising farmer profits by managing weeds using rotations: OM1 for a single field; and, OM2 for a landscape of multiple fields. Here, we introduce the underlying assumptions and settings of these contrasted illustrative landscapes, and describe the main sub-models used in the OMs to model the functions of weed population dynamics and dispersal, crop yield and the farmers' profit. We then describe the specifications of the two OMs and summarize selected scenarios representing the main ecological and economic uncertainties.

Underlying assumptions and illustrative landscapes

We consider a rotational system where farmers can freely choose between growing winter wheat or winter oilseed rape. In OM1 we assume that the landscape is represented by a single, isolated field in consecutive years (Figure 11a). In OM2, the fields are placed close to each other in a rectangular grid that allows for ecological interdependencies between the fields due to weed seed dispersal. For simplicity, we specify OM2 as having four fields arranged as a 2 × 2 chessboard-like landscape (Figure 11b). To avoid introducing confounding factors such as field size and heterogeneities in soil quality, we

assumed that all the modelled fields in OM1 and OM2 are exactly similar and homogeneous, differing only in their placement within the landscape. Where farmers decide to grow wheat in field i (f_i) in period t, $x_{i,t}$ = 1, otherwise oilseed rape is grown and $x_{i,t}$ = 0. The distribution of crop choice evolves over time as a consequence of crop rotational decisions. The model proceeds in annual time steps and in each yearly period, rotational decisions affect three sub-models describing weed population dynamics and dispersal, crop yield and the farmers' profit.
[Figure 11 here]

Main sub-models

Weed production and dispersion

The models are based upon a simplified model of the life cycle of a weed in which the seedbank, standing weed and seed rain compartments of weed populations are described (Figure 12). The weed plants in field f_i in the current period (t), $wp_{i,t}$, is equal to the combination of the seedbank in f_i in the period t-1 (sb_{t-1}), the mortality of weed seed (sm), the germination rate from the seedbank (gr) and weed plant mortality (pm), such that:

$$wp_{1,i,t} = sb_{1,i,t-1} \times (1 - sm_1) \times gr_1 \times (1 - pm_1) \qquad 1$$

$$wp_{2,i,t} = sb_{2,i,t-1} \times (1 - sm_2) \times gr_2 \times (1 - pm_2) \qquad 2$$

where the subscripts 1 and 2, in the weed plant variable, represents grass and broadleaf weeds respectively.
[Figure 12 here]
The weed seeds produced in f_i in the current period, $s_{i,t}$, are product of the number of weeds, $wp_{i,t}$, and weed seed reproduction rate, sp, as in equations (3) and (4):

$$s_{1,i,t} = wp_{1,i,t} \times sp_1 \qquad 3$$

$$s_{2,i,t} = wp_{2,i,t} \times sp_2 \qquad 4$$

The weed seedbank in f_i in the current period, then becomes equal to those surviving seeds that do not germinate in the seedbank at t-1, $sb_{i,t-1}$, and the contribution of seeds dispersed in the landscape in the current period, as shown in equations (5) and (6):

$$sb_{1,i,t} = sb_{1,i,t-1} \times (1 - sm_1) \times (1 - gr_1) + \sum_{j=1}^{n} D_{1,j,i,t}(f_j, f_i) \qquad 5$$

$$sb_{2,i,t} = sb_{2,i,t-1} \times (1 - sm_2) \times (1 - gr_2) + \sum_{j=1}^{n} D_{2,j,i,t}(f_j, f_i) \qquad 6$$

where $D_t(f_j, f_i)$ is seed dispersal, as defined in equations (7) and (8):

$$D_{1,j,i,t}(f_j, f_i) = s_{1,j,t} \times p_1(\sqrt{(xc_j - xc_i)^2 + (yc_j - yc_i)^2}) \quad 7$$

$$D_{2,j,i,t}(f_j, f_i) = s_{2,j,t} \times p_2(\sqrt{(xc_j - xc_i)^2 + (yc_j - yc_i)^2}) \quad 8$$

where $xc_i(xc_j)$ and $yc_i(yc_j)$ are the spatial coordinates of field i (j). Dispersal of seed following reproduction moves the seeds around the landscape according to the dispersal kernel function, $p(dist)$, which describes the probability that a dispersed seed arrives at a distance $dist$ away from a source weed plant. Different assumptions for the dispersal function have been used in the literature, including Gaussian, Weibull, Exponential and bivariate Student's *t* distributions (Crossman et al., 2011; Dauer et al., 2007; Paradis et al., 2002). Here we adopt the exponential distribution for this study, as a simple distribution with only one parameter (λ) that has clear ecological implications and is equal to half of the average dispersal distance (Austerlitz and Smouse, 2001), as shown in equations (9) and (10):

$$p_1(dist) = \frac{1}{2\pi\lambda_1^2} e^{-\frac{dist}{\lambda_1}}, \lambda_1 > 0 \quad 9$$

$$p_2(dist) = \frac{1}{2\pi\lambda_2^2} e^{-\frac{dist}{\lambda_2}}, \lambda_2 > 0 \quad 10$$

For analysis, we assume that when farmers grow wheat they will use herbicides to control broadleaved weed plants. Similarly, when they grow oilseed rape they will use herbicides against grass weeds. Through a wheat and oilseed rape rotation, therefore, farmers can control grass and broadleaved weed via crop choice, depressing those weeds that are most damaging to their overall yield and in turn profits.

Crop yield model

The yield of the crop depends on the competition between crop and weeds. Fields with high densities of weeds will depress crop yield. Following Pannell et al. (2004), we assume that the wheat yield in f_i, $Yw_{i,t}$, can be calculated as:

$$Yw_{i,t} = Yw_{max} \times \frac{(d_{0,w} + a_w)}{d_{0,w}} \times \frac{d_{1,w,t}}{a_w + d_{1,w,t} + (k_w \times wp_{1,i,t} + k_0 \times wp_{2,i,t})} \times m_w + (1 - m_w) \quad 11$$

where Yw_{max} is the yield of wheat in fields free of weeds, $d_{0,w}$ is a standard wheat density, $d_{1,w,t}$ is the realised wheat density, $wp_{1,i,t}$ and $wp_{2,i,t}$ are the densities of grass weeds and broadleaved weeds, respectively, m_w is the maximum proportion of wheat yield lost at very high weed densities; a_w is wheat specific constant, and k_w and k_o are constants for the competition between grass weeds and broadleaved weeds and the wheat crop, respectively. The yield of oilseed rape can similarly be described as:

$$Yo_{i,t} = Yo_{max} \times \frac{(d_{0,o} + a_o)}{d_{0,o}} \times \frac{d_{1,o,t}}{a_o + d_{1,o,t} + (k_w \times wp_{1,i,t} + k_0 \times wp_{2,i,t})} \times m_o + (1 - m_o) \quad 12$$

Profit calculation models

The profit that the farmer accrues, π, can be calculated as the difference between the revenue from sales of his crop and the costs of production. Crop sales are simply the product of crop price and yield. We assume that the market price of a crop is not affected by output change in the landscape and is exogenous. The crop yields are obtained from the crop yield functions in equations 11 and 12. The farmers current profit can be calculated as:

$$\pi_t = P_w \times yw_t + P_o \times yo_t - cw_t - co_t \quad 13$$

where P_w and P_o are the exogenous prices of wheat and oilseed rape, respectively. yw_t and yo_t are the total crop yield of wheat and oilseed rape, cw_t and co_t are the total farming cost of wheat and oilseed rape. Using CW and CO as the unit farming costs (per ha), including the costs of herbicides in the wheat and oilseed rape, we get:

$$yw_t = \sum_{i=1}^{N} x_{i,t} \times Yw_{i,t} \quad 14$$

$$yo_t = \sum_{i=1}^{N} (1 - x_{i,t}) \times Yo_{i,t} \quad 15$$

$$cw_t = \sum_{i=1}^{N} x_{i,t} \times CW \quad 16$$

$$co_t = \sum_{i=1}^{N} (1 - x_{i,t}) \times CO \quad 17$$

where i = 1 and i = 2 for OM1 and OM2, respectively. We can thereby optimise the arrangement of the two crops in both time and space to maximise the economic benefits from production.

Results

It is clear with these initial results from model OM1 that simple rotation patterns are not economically optimal and can be improved by changing the order and frequency of wheat and oilseed rape in rotations (Figure 13). With the optimal model, counts of weed plants and seeds in the seedbank can be minimised over the long term, while crop yields can be maximised compared to the simple rotations (Figure 14). When considering the spatial, as well as temporal arrangement of crops, model OM2 shows that spatial synchrony does not maximise economic return. Instead, the optimal arrangement shows that asynchrony in both space and time achieves the highest farm productivity (Figure 15).
[Figures 13 – 15 here]

Our results demonstrate that simple and synchronous rotation patterns are not economically optimal for managing land. However, our results do not allow us to state clearly either what those optimal rotations are, or the ecological-economic rules for optimisation. Further work is needed to find simple rules for farmers to allow them to make good decisions that are close to being optimal. The importance of spatial asynchrony also suggests that farmers need to consider the wider landscape and so work together in planning rotations to manage yield and weeds for each other's benefit. Finally, optimization approaches, such as this, could be applied to other ecosystem services and so provide a multifactorial approach to planning rotations.

7 The Biodiversity and Ecosystem Services of arable fields undergoing crop rotation

There are many different ecosystem services that are derived from the biodiversity present in agricultural systems, and these could be affected by rotations. Following from the previous section on the economic impact of weeds on yield, here we consider farmland weeds and their ecosystem services and dis-services of weed plants as part of the ecological evaluation. Weed plants have a major role in the productive functioning of arable agricultural ecosystems (Section 6). On the one hand, weeds provide agricultural dis-services by competing for nutrients with the crop and thereby cause marked yield loss. Farmers view many of these weed species as pests, and chemical herbicides are still the predominant means of pest weed control in conventional EU agriculture, accounting for 42.3% of all pesticides in 2010 (www.faostat.org). On the other hand, weeds and their diversity support much of the biodiversity and ecosystem services that are experienced in agriculture (Marshall et al. 2003, Pocock et al. 2012). Weed plants and weed seeds provide important food sources for pollinators (Storkey and Neve 2018) and farmland birds (Gibbons et al. 2006, Moorcroft et al. 2002, Wilson et al. 1999), and the physical structure of the weed plants provide refuges for many invertebrates that in turn provide pest control services (Storkey and Neve 2018, Staudacher et al. 2018). Carabid beetles are important natural enemies of many pests in agriculture, including aphids and slugs (Bohan et al. 2000, Gray et al. 2021, Roubinet et al. 2018, Winder et al. 2005), that often use dense stands of arable weed plants as refugia. Carabids consume weed seeds (Frei et al. 2019) and recent work has suggested that predation by carabid beetles of weed seeds at the soil surface can cause significant declines in the size of the weed seedbank, indicative of regulation, over a whole season of growing and at continental scales (Bohan et al. 2011a, Carbonne et al. 2020). Striking the appropriate balance between the service and dis-service of weeds will be important, therefore, because it is at the nexus of our competing needs for food, the environment and biodiversity, and any acceptable sustainable agricultural system proposed for the future, and particularly systems that reduce reliance on herbicides.

We know from previous work that the numbers and types of weed seeds in the seedbank are driven by rotations (Bohan et al. 2011b), and that crop choices determine the numbers of weeds that germinate from the seedbank (Smith et al. 2008, 2010) to cause crop loss and support biodiversity. Our conceptual model for these interactions is shown in Figure 16 and based upon past research and our conjectures for the likely interactions between rotation, carabid and weed effects. At the centre of the conceptual model is a simplified weed life cycle, similar to that used in Section 6 (Figure 12). Weed seeds in the seedbank at t_0 become seeds at t_{+1} either directly by remaining dormant or indirectly by germination to standing weeds that reproduce and set seed as the seed rain that can re-enter the seedbank. The initial starting seedbank, t_0, is in part driven by the history of crop rotation in the field (Bohan et al. 2011b). Effects on the germination to the standing weeds and to the seed rain include the crop currently sown in the field that provides the general environment, with differences in this environment presumably being larger between crops and crop types than within crop types (Bohan et al. 2011b). The current crop and the standing weeds, and implicitly therefore past crop rotation, also provide the environment in which carabid beetles occur, with certain crop and weed combinations presumably supporting higher counts of carabids. These carabids, foraging at the soil surface will then intercept some of the seed rain, and seed predation pressure will prevent some seeds from re-entering the seedbank at t_{+1}. Importantly, this seed predation pressure is not a simple number, but is determined by the diversity of weed seed and carabid species present, each with their specific properties. It is here that the biodiversity of weeds and carabids enters the conceptual system.

Figure 16 suggests a number of simple hypotheses that could be tested in analyses of existing data and then validated using data from replicated field experimentation. The first hypothesis, H_1, is that the initial seedbank, t_0, is related to crop rotational history. For H_2, the abundance of standing weed plants, whether totals, dicotyledon or monocotyledons, is related to the current crop and potentially to the history of crops grown in rotation. Hypothesis 3 (H_3) would be that carabid counts are related to the current crop. Finally, H_4 would be that the final seedbank, at t_{+1}, is related to the initial seedbank, t_0, and the current crop.

[Figure 16 here]

The conceptual model in Figure 16 forms the basis of our ecological modelling work presented here and detailed in Schmucki et al. (2020). Previously, we developed a model based upon our current understanding of carabid beetle species' preferences for different species of weeds (Pocock et al. 2020). This uses expectations of feeding profitability that are determined by body size and we scaled up these interactions to predict food webs for fields with known weed seed and carabid data. The quantitative links of the food webs can then be used to calculate inferred seed predation pressures for the weed seeds in fields. Here, we present a structural equation model (SEM) fitted to data from a large-scale field sampling of carabids and weed in arable cropping systems (Schmucki et al. 2020). The SEM both formalises the conceptual model and includes inferred seed predation pressure to test and confirm whether existing field data support our conception. By doing this we explicitly link and integrate rotational management and weed and carabid biodiversity to the services provided by this ecosystem and provide an integrated understanding of their impact on weed management in arable fields. In the final part of the Section, we test both the hypotheses of the conceptual model and the findings from the SEM using new data that was created to examine effects between rotations, carabids and weeds.

Weed, carabid and rotational data used for the modelling

The data used for the modelling in Section 7 come from the Farm Scale Evaluations (FSEs) of genetically modified, herbicide-tolerant crops (Firbank et al. 2003). These field trials came about in the late 1990s and early 2000s due to a fear that control of weeds in GMHT crops tolerant to broad- spectrum herbicides might be so efficient that it could help to clean up previously weedy fields (Watkinson et al. 2000), exacerbating long-term declines in weeds and the wildlife depending on them (Hails 2000). The trials were notable because they were provoked by public acceptability of environmental impact and because they were placed in commercial farm fields. At that time, four GMHT crops were close to market and were trialled in the FSE. These were three crops tolerant to glufosinate-amonium (a spring-sown maize and a spring- and a winter-sown oilseed rape), and a spring-sown beet (forage and sugar beet) tolerant to glyphosate. The four crops were tested in 256 farm fields, across Great Britain, using a split-field design with the GMHT crop on one side and a conventional cultivar of the same crop on the other. Prior to the sowing of the conventional and GM cultivars, soil seedbank samples were taken in both halves of all fields to establish the size and composition of the initial weed seedbank, using germination (Heard et al. 2003; Bohan et al. 2005). Similar soil sampling established the size of the follow-up weed seedbank at the end of trial, after the harvest of the conventional and GM crops. Sampling for the carabids, the standing weeds and the weed seed rain was done on up to twelve transects running from the edge of the fields to the field centres (Firbank et al. 2003). Carabid sampling used pitfall traps placed at 2, 8 and 32 m into the crop on four transects, on three sampling occasions during the year (Brooks et al. 2003; Bohan et al. 2005). Carabids were counted and identified to species, and then summed across the year to create a year total for analysis. Counts of standing weeds were done using quadrats placed at 2, 4, 8, 16 and 32 m on all twelve transects at various times during the trial (Heard et al. 2003; Bohan et al. 2005). These weeds were identified to species within the field and their numbers summed to a year total for analysis. Weed seed rain was estimated at 2 and 32 m on four transects using seed rain traps, as described in Heard et al. (2003). The trapping commenced when anthesis was observed in any weed species and continued until crop harvest. The traps were emptied approximately every two weeks. All seeds were identified to species and those classified as viable were summed to create a year total count of seed rain (Heard et al. 2003; Bohan et al. 2005). The analyses of rotation in Section 7 are limited to 168 fields, for which sufficiently detailed rotation history was available (Bohan et al. 2011b). We also exclude from analysis all data for carabids and weeds from the GM field halves.

Modelling the diversity of carabid-weed seed interactions

We have information from the FSE fields about the seeds present and the carabids present. We do not have information on which carabids feed on which seeds, despite this being a crucial attribute to determine the predation pressure on seeds. Experimental trials have shown that larger carabids tend to prey upon larger seeds (Honek et al. 2003). Here we constructed networks of the predicted interactions of carabids feeding on seeds by inferring the strength of the interactions between seeds and carabids present in each field. This was based on frequency-dependant foraging (Gendron 1987) and size-dependant preferences determined from the literature (Honek et al. 2003; Petit et al. 2014). Full details of the methods are presented elsewhere (Pocock et al. 2020).

These inferred networks need to be validated, but while direct information on carabid-seed feeding is difficult to obtain from the field, molecular trophic analyses have been applied to detect prey DNA in the gut regurgitates of carabids (Sint et al. 2018, Wallinger et al. 2015) and simple food webs have been constructed from DNA analysis of carabid gut contents (Frei et al. 2019). In addition, the predicted networks and metrics can be tested and verified with other approaches and can be used in analyses of the robustness and resilience of biodiversity and ecosystem services (Ma et al. 2019, Pocock et al. 2012). One of the network-derived measures that we calculated, which can be used in validation, was the seed predation pressure. For this, we took the weighted interaction strengths (i.e., the number of seeds consumed by the assemblage of carabids present, taking into account carabid seed preferences, the community of seeds present, and carabid energetic requirements), summed these across each type of seed, and divided by the density of that seed.

In our research, we produced inferred networks for 255 fields of the FSE with data on carabid and seed abundances and calculated the seed predation pressure (Figure 17). We tested for the effect of crop type, seed size and abundance on predation pressure, with the field as a random effect for intercept and slope to take account of variation in the size and direction of the overall effect. We found that the predation pressure for each seed genus in each field varied substantially (Pocock et al. 2020): smaller seeds tended to have lower predation pressure than larger ones (overall effect size = 0.084, S.E. = ±0.018; $P<0.001$), and it varied by the crop type: beet fields had the highest predation pressure ratio; maize was no different to beet (effect size compared to beet = -0.263, S.E. = ±0.199), spring-sown oilseed rape was lower (-0.826, S.E. = ±0.183 compared to beet) and winter-sown oilseed rape was

lowest (-1.443, S.E. = ±0.185 compared to beet). Here, we use these networks-derived measures of seed predation pressure, to inform an SEM analysis of the FSE data, thereby incorporating biodiversity into our consideration of the effects of rotation.
[Figure 17 here]

Modelling of rotationally-derived ecological functions of the regulation of weeds

To model both the direct effects of crop rotations on weed dynamics and their indirect effects via the predation of weed seeds by carabid beetles, we developed a structural equation model (SEM) around the conceptual model presented in Figure 16. We combined the predictions of carabid predation pressure described in Section 7, above, and Pocock et al (2020), the FSE field trial data-sets (Scott et al. 2012a-d) and the rotational history documented for 168 FSE fields, with sequences of crops sown for up to nine years prior to the FSE study year (Bohan et al. 2011b). In each of these fields we used data for the initial (t_0) and final (t_{+1}) weed seedbanks, the total numbers of standing weeds counted, the total for the seed rain set by those weeds and counts of the carabids in the pitfall traps (Brooks et al. 2003, Heard et al. 2003, Bohan et al. 2005). For our analysis, we only used the data for the conventional halves of each field monitored in the FSEs trials. Details of the methods are available in Schmucki et al. (2020).
The core of the SEM was built around a weed life cycle that linked the seed counts in the seedbank, collected at t_0 and t_{+1}, to the densities of standing weeds and the number of arable weed seed in the seed rain collected over the crop growing season (Figure 16). This weed life cycle was then explained in terms of management and biotic components. Rotational management (crop history) was used to explain the density of the initial seedbank, t_0. Management of the current crop, namely the four crops used in the FSE field trials, was used to explain both the number of weed plants and the activity-density of carabid beetles feeding on seeds weeds. The number of weed plants growing in each crop field was then used to explain the number of seeds that were rained back onto the soil surface and the activity-density of carabid beetles feeding on seeds. The biotic effect of carabid beetles on seed density, calculated as carabid predation pressure (Section 7, Pocock et al. 2020), was then used to explain how much seed entered the seedbank at t_1. To account for the seeds that remain dormant during the cropping season (Mahé et al. 2020), the SEM also included a link between the seedbank sampled at t_0 and at t_{+1}. Finally, we added a relationship between the density of standing weeds and the seedbanks at t_{+1} to account for the portion of the seed rain that was not captured by the FSE seed rain samples.
The rotations used in the SEM were not treated as the detailed sequences of crops or crop types (Bohan et al. 2011b). Rather, we summarised each sequence with a simpler, ordinal index representing the number and consecutiveness of cereal crops and/or the number of winter-sown crops observed in the 3 years preceding the FSE field trials (t_0) (Schmucki et al. 2020). We also used simple factor levels to code the four crops grown in the FSE trials (current crops in Figure 16), using spring oilseed rape as baseline and coding the three other crops as binary variables, of zero or one. Fitting complex SEMs can be challenging and requires large data-sets to reach convergence and produce reliable confidence intervals. However, recent computational advances have led to the development of Bayesian approaches for SEMs (Merkle et al. 2020) that allow for the fitting of complex models as they address issues of non-convergence and improve estimations of parameter confidence intervals (Smid et al. 2020). We therefore fitted our SEM within a Bayesian framework in *R* (R Core Team 2020), using the MCMC sampler Stan 2.21-0 (Carpenter et al. 2017), in combination with the *R* packages lavaan 0.6-7 (Rosseel 2012) and blavaan 0.3-10 (Merkle et al. 2018).
[Figure 18 here]

The results show that the seedbank at t_0 was directly related to the history of cereal- and winter-sown crops, in the previous three years (Figure 18; Hypothesis H_1). This ordinal index only explained 5% of the variance observed in seedbank at t_0, however. The effect of rotation was mainly driven by the recent history in cereal crops, with a quadratic effect pointing toward some optimal sequence configurations (Figure 19). As expected, the abundance in standing weed was partly explained by both the seeds in the seedbank, at t_0, and the current crop (Figure 18, H_2). The standing weed contributed to the seedbank at the end of the growing season (t_{+1}), both directly and through the seed rained onto the soil surface captured in the FSE seed rain sample (Figure 18). Interestingly, fields with higher densities of standing weeds had higher counts of seed-eating carabid beetles. The density of carabid beetles was also influenced by the crop that was grown in the field, with higher counts in fields of beet and lower counts in winter oilseed rape (Figure 18). This result confirms the hypothesised effect of field management on the activity-density of seed-eating carabid beetles (H_3). The carabids then have an effect on the seedbank at t_{+1}, mediated by the carabid predation pressure described in Section 7 (Figure 18).

[Figure 19 here]

Overall, the SEM explains 43 % of the variance observed in the density of seed collected in the seedbank at t_{+1} (Schmucki et al. 2020). This indicates that the choice of crops and their sequence can contribute to weed management through their effects on the seedbank and standing crop, but also on the density and composition of the carabid beetle community and the seed predation pressure they apply on the weeds. While crop management, including rotation and herbicides remains the main driver affecting the density of weed seeds in the seedbank, carabid predation pressure provides a regulation service that significantly contributes to reducing the number of seeds that accumulate in the seedbank. The positive effect of increased density of standing weeds on the activity-density of the carabids suggests that farmers and agronomists might consider weed management approaches that do not eradicate arable weeds from the cropping system, as part of moves towards a more sustainable agriculture (MacLaren et al. 2020), but rather control weed population size and provide resources to biocontrol agents such as carabid beetle feeding on seeds. This could be done by the development of crop rotations that support the ecosystem service of carabid weed seed regulation of weed seeds in the seedbank, potentially avoiding weed outbreaks and offsetting farmer-dependency on herbicide inputs.

Field validation that rotations affect weeds and weed seed predators

In the co-construction of acceptable rotations, model-based predictions of rotational effects, whether ecological, social or economic (see preceding sections; Poggi et al. this issue), would require testing and validation. This means that experimentally replicated validation and testing should be conducted where possible. Discussions with farmers have also indicated that this experimentation should be done in commercial farm fields, in what they deem to be real situations of management, if we are to demonstrate that the effects we would want can be put into practice. In many cases this would mean that experiments should test rotational predictions in fields where those rotations are already being used.

There is a long history of testing for the effects of management on crop performance at field scales. Much of the foundation of ecological statistics was developed, most notably at Rothamsted Experimental Research Station in the UK by Ronald Fisher (Fisher 1972, Yates 1964), with a strong component of farmer demonstration. The aim was to show that any new management, say the application of fertilizers or herbicides, had both an agronomic and statistically valid effect. For a long time, such experimental testing of management effects on biodiversity and ecosystem services was

rather rare and largely confined to small-scale eco-toxicological studies of pesticides. More recently, this type of testing has been growing in importance with concerns for the impact of agricultural management on the farmland environment and biodiversity (Mancini et al. 2020).
One of the first and largest examples of this approach to understanding the effect of a new management on farmland biodiversity, prior to its adoption, comes from the FSE, which have already contributed data to our work in Section 7. Power analyses of the FSE provided a guide of about 60 fields per crop for observing management change effects (Perry et al. 2003, Clark et al. 2003, 2007). These requirements drove the costs of the FSE above £6 million, in the early 2000s, and such costs cannot be borne for every proposed change in management or rotation. Rotations also have landscape-scale effects that propagate out from the focal field in both space and time; much as was modelled in Section 6. These are difficult to study at the levels of replication suggested by the FSEs and rotational testing will likely be limited to the field-scale, with extrapolation of the likely landscape effect being an exercise in modelling (see Poggi et al. this issue). The field experimental validation that we conduct here reflects this scale and cost. We have made no attempt to validate large-scale spatial effects across the landscape. We also do not study specific co-developed rotations because the fieldwork had to start in advance of these being available to fit into the project timeline. We do, however, take the principles and basics of the design of the FSE for the experimental studies we present with the goal of investigating whether rotations have effects on weeds and carabids and their ecology. We used this experiment validation to test the four key hypotheses proposed from the conceptual model (Figure 16) and the SEM.

Field methodology

A total of 85 fields were sampled in Hungary, in 2016 and 2017, and 23 fields in the Cote d'Or region of Bourgogne-Franche-Comté (Bgn), France, in 2017 and 2018, for standing weeds and carabids. In the French fields, the weed seedbank was also sampled after cropping in 2017 and 2018 to provide an evaluation of the size and change in the seedbank across one growing year. All fields followed the standard rotation ordinarily used by the farmer and no attempt was made to otherwise modify their cropping pattern or agronomic management.

In-field transects

Sampling was conducted on two, 32 m long transects running from the field margin towards the centre of each field, as per the FSEs (Haughton et al. 2003, Bohan et al. 2005). A transect was placed in the direction of sowing and the other orientated perpendicular to the direction of sowing. Soil sampling was done at 4 and 32 m points, from the margin, along the transects to estimate the weed seedbank (Heard et al. 2003). A single pitfall trap was installed at 4m, 8m, 16m and 32m along all transects (Brooks et al. 2003). Adjacent to each pitfall trap, a 50cm per 50cm quadrat was placed for counting and identifying standing weeds (Heard et al. 2003).

Standing weed counts

In both Hungary and France, the standing weeds were identified in the field to species level and then counted. Counts for monocotyledon, dicotyledon and total weeds were then formed across the year of sampling.

Seedbank counts

France: The weed seedbank was assessed using the methods described in Heard et al. (2003). Seedbank abundance was estimated by taking 5 soil cores (1.5 L in total between 0-20 cm depth) at the 4 and 32 m sampling points along the transects. The seedbank was estimated by germination of soil samples in a greenhouse under controlled conditions (18/15°C day/night temperature regime with 12:12h light:dark cycle). Counting and species identification of the germinated seeds in the samples were done up to 18 weeks after sample preparation. Weed seeds germinating from the soil samples collected in 2017 and 2018 were identified to species and summed to a total count of seeds per sampled field.

Pitfall trapping

Hungary: Carabids in the Hungarian pitfall trapping were counted to give a total number of carabids per field across the year.
France: Beetles were sampled in at two sampling sessions, May and June, in 2017 and 2018. Pitfall traps were opened for 4 days during sampling. Carabids were identified to species, and these were then aggregated to a total carabid count per field per year for comparison with the Hungarian data.

Statistical approach

The data were analysed with linear mixed-effects models, using the *lme* function of the *lme4* package and maximum likelihood estimation in *R* (R Core Team 2020). All modelled count metrics for the weed seedbank, standing weeds and carabids were analysed as $\log_{10}$-transformed data with the Gaussian error distribution. Rotations were analysed as (1) the richness of crops in a three-year sequence, between year t_{-1} and t_{-3}, or (2) a rotational factor, following Bohan et al. (2011b), which was a simple factorial combination of crops. Rotational factors were created across two years with a number of levels that reflects the crops grown in the sample of fields that year. In year t_{-1}, a one-year rotation would have 4 factor levels if four different crops were grown across all fields in that year. A two-year rotational factor is therefore the combination of the factor levels in the first year of the rotation, year t_{-1}, and the preceding year, year t-2. The current crop in each field (i.e. year t) was also included as a factor in the model. We tested the following four hypotheses, as proposed by our conceptual model (Figure 16).

Hypothesis 1. Rotation affects the magnitude of the initial weed seedbank

Modelling the effects of past cropping on the initial weed seedbank, taken prior to the sowing of the current crop in France, used the rotational factor or rotational diversity as fixed effects and a factor for the year of study as a random effect.

Hypothesis 2. Rotation and current crop affect the standing weeds

Standing weed counts in Hungary and France were modelled as monocot, dicot and total weed counts. A factor for the current crop and for the prior rotational factor or diversity were modelled as fixed effects. A country factor, nested within the year of study, was treated as a random effect.

Hypothesis 3. The current crop and past rotation affect carabid counts

Carabids were modelled with the current crop and prior rotational factor or diversity as fixed effects. Random effects of country, nested within the year of study were used.

Hypothesis 4. Only the current crop, and not past rotation, affects the change in the seedbank

Seedbank change was modelled using the logged seedbank counts at the end of the growing season. The initial seedbank was then fitted alongside rotational factor or diversity as fixed effects. No random effects were specified. We would note that this model could have been done using simple or generalised linear modelling, and the *lme* approach was maintained for consistency.

Results

We found that the size of the French weed seedbank was determined by the prior rotation (Table 8). With the data-set available, we found that a single year rotational factor was significant, but that adding further years of rotational factor information did not improve the fit (ΔAIC = 0.43, p = 0.078). The diversity of preceding three years of rotation had no effect on the size of the seedbank.

[Table 8 here]

The total number of standing weeds observed in the fields of France and Hungary was found to be related to the current crop as a factor and up to two years of prior rotational factor (Table 8). The dicot component of the standing weed community showed a similar response to the current crop and two years of rotational factor, but for the monocots it was the current crop and one year of prior rotation with further years of prior rotational factor significantly reducing the quality of fit (ΔAIC = -1.60, p ≤ 0.02). The total number of standing weeds was found to be related to the current crop, as a factor and rotational diversity. Dicots were similarly affected by the current crop and rotational diversity, as were the monocots for the current crop and rotational diversity.

Carabid counts were significantly related to the current crop and two years of prior rotational factor Table 8). There was no effect of rotational diversity on carabid counts.

The change in the magnitude of the seedbank to the end of the growing year was significantly related to the initial seedbank at the start of the growing year and the current crop (Table 8). The inclusion of one year of rotational factor in the model was significant, but prior rotational diversity was unimportant.

Validation of the rotational model

This analysis of field sampling data shows that it is possible to conduct field experiments to validate ecological expectations driven by rotation in farm fields. We find that the expectations of the rotationally explicit, conceptual model and SEM modelling are largely borne out by the field data for both weed and carabid metrics. Following the steps in Figure 16, in turn, we find that the size of the initial seedbank in France was related to prior rotation as expected. The subsequent counts of weeds that germinate from this initial seedbank, whether considered as monocot, dicot or weed totals, was related to the current crop, which presumably determined the conditions of germination, and past crop rotation (Bohan et al. 2011b). The activity-density of carabids trapped within the fields, during the year, was found to be related to the current crop being grown within that field. The SEM and past studies predict this effect and provide explanations that the current crop is a good proxy both of the conditions within a field that supports carabids (Section 7; Brooks et al. 2011) and the amount of weed seeds that are present on the soil surface to attract carabids (Bohan et al. 2011a, Petit et al. 2013, Westermann et al. 2009). The SEM would also suggest that there should be a relationship between rotation and the counts of carabids in the field, but we do not find evidence for this here. Finally, the analysis demonstrated that while the final seedbank was related to the size of the initial seedbank and the crop grown during the year, there was no effect of past rotation (see also Bohan et al. 2011b). Effectively, the size of the initial seedbank is determined by the reproduction of weeds across a number of years, but within any one of those years the rate of reproduction or change in the seedbank is only determined by the crop grown, and presumably the amount of predation by carabids (Section 7).

Representing crops in rotations within this model (either as a rotational factor or rotational diversity) gave broadly similar results. Both metrics reflect the numbers of crops that were grown in each rotation. We would have expected, therefore, that there would be considerable similarity in their

explanatory effects. Where they differ is that the rotational factor levels are created through consideration of each year in the rotation, and thus retains information about the structure and ordering of the crops in the rotation, which is lost when calculating simple richness. It is the ordering of the crops in a rotation that farmers use to produce an agronomic effect, such as disease and weed control (see Section 6), and has been found to be important in both the SEM model and past rotational modelling (Bohan et al 2011b).
These experimental findings support our belief that predictions of ecological models linked to future rotational scenarios could be validated in fields where those rotations are already used. These tests validate expectations of the SEM model that rotations drive carabid and weed populations. Moreover, this validation was done on commercial farm fields where farmers have otherwise continued their habitual agronomic management of the crops. The scale of the experimental sample, at between 23 and 108 fields, depending on whether we considered field data from France alone or France and Hungary together, was also of the order of that shown in the FSEs to be sufficiently powerful to measure effects (Clark et al. 2005, 2007).

8 Selecting agronomically, economically and ecologically acceptable future rotations

The final step of the workflow is to work as a group of stakeholders (farmers, agronomists and others) to select from the agronomically acceptable rotations devised in Section 5, those that also meet economic and ecological acceptability criteria under future climate. In developing these acceptable future rotations, one of our aims is to inform policy making, within the remit of legislation such as the EU Common Agricultural Policy greening measures (European Commission 2020). Therefore, policy makers could have a valuable role to ensure policy-relevance and to use the results to help shape policy interventions, although the design of the future rotations should be farmer-led.
The information that users of the workflow require crosses multiple spatial, temporal and organisations scales of ecology, economics and agronomy. The ecological information scales from individual carabid species and their preferences for particular weed seeds, up to predictions for weed seed regulation at national scales (Carbonne et al. 2020, Schmucki et al. 2020). The economic modelling provides information on how the organisation and synchrony of rotations across fields in a landscape affects yield and economic sustainability. The multinational mapping demonstrates that the structure of the cropped components of the landscape is intimately related to the rotations used in the landscape. This information is of use because it allows us to identify landscapes where there is opportunity to introduce new rotations, to improve landscape diversity and sustainability in the face of climate change allowing this workflow to be scaled up to large spatial scales relevant for policy design. Acceptability could and probably should be evaluated at all these scales.
The process of selection of acceptable rotations should consider a wide range stakeholder-actors. These might be actors at the local scale, including agronomists who advise farmers and residents who live near to arable fields. At the scale of the landscape, the actors could include water companies, conservation groups and farming cooperatives. At wider scales still, the stakeholders taking part might include actors from across the arable industrial supply chain. Opening up discussions to stakeholders at multiple scales will allow us to consider the multiple values of farming for sustainable food production, livelihoods, and the cultural and biodiversity benefits of farming. However, for the workflow, we recommend that the discussion of the acceptability of rotations should be kept simple, by limiting the selection of rotations to the landscape scale, in those landscapes identified through the mapping, and allow wider scale decision making to be guided by policy.

At the landscape scale, the weighting applied to the ecological and economic information in the selection of acceptable rotations should emerge from focus groups made up of scientists, farmers, agronomists and other locally important actors. Importantly, this weighting could change between the different landscapes under study. This process of discussion between actors could also be governed by a conflict management process, as discussed by Skrimizea et al. (2020). Rather than differences in opinion between actors being seen as a bad thing, the conflict approach sees the frank exchange of views as necessary and a potential source of creativity for deriving solutions. Critically, here, there is no privileged information only available to a few because all stakeholders who participate in the selection process are presented with the same agronomic, economic and ecological information upon which to form their opinion and arrive at shared decisions.

9 Perspectives

There is a need for European agriculture to develop new arable crop rotations that would support adaptation to climate change by being agronomically and economically beneficial to farmers, with benefits to biodiversity via ecosystem service provision. In this paper, we propose a workflow that could be used to achieve this (Figure 1), via the co-development of novel future rotations as scenarios of adoption using a web-based tool that integrates farmer agronomic knowledge and expertise; the *Future Rotation Explorer*. Then, economic and ecological modelling and experimental validation of the rotational scenarios is used to select with farmers those developed rotations that also meet objective standards of economic return and ecosystem service delivery. Although the workflow has not been tested in its entirety, each farmer-facing step has been explored in discussion with individual farmers or in focus groups. Our discussions with farmers suggest that this co-development workflow will be of great practical benefit as they adapt to climate change.

There are several places where new work could support improvements in the workflow we present in this paper. Currently, co-development of future scenarios of rotation is limited by the availability of crop models. Only nine crops were represented in the *FRE*. These are modelled in the WOFOST models (de Wit et al. 2019) that are used by the Joint Research Centre (JRC) for reporting to the EU (https://agri4cast.jrc.ec.europa.eu). It would be valuable to extend this to a larger number of crops, including those that could be grown in the future. Some appropriate crop and varietal performance models already exist (see Jeuffroy et al. 2014), but others will need to be developed.

The next step of the workflow was to understand the economic and ecological consequences of rotations. For the economic modelling, we demonstrated that the rotational history of crops affects yield in the current year. Researchers could calculate these effects on yield for novel rotations by evaluating existing data from other regions where those rotations are used. This would require information on per-field crop yield, which is increasingly collected at harvest but is often difficult to access. For the ecological modelling, we considered weeds and predicted the ecosystem service of regulation of the weed seedbank by carabid beetles and in the future other ecosystem services should be added to the workflow. We showed that predictions made from these ecological models can be validated in rotationally-explicit trials in commercial farm fields that can serve as demonstrations to other farmers.

The ecosystem services could and should be added to the workflow include any economic and ecological effect that could be linked to crop rotation and/or the landscape pattern of crops. Ecological examples might include the storage of carbon in the soil (Land et al. 2017), insect pests (Zohry and Ouda 2017) or pollination (Hald et al. 2001, Marshall et al. 2003). Linking the economic and ecological modelling in this way would build a broader battery of indicators of ecosystem service change, knowledge of ecosystem service interaction (Balvanera et al. 2016, Bennett et al. 2021, Gray et al. 2021) and agronomic change, such as reducing pesticide use (Möhring et al. 2020).

Our proposed co-development of future rotations seeks to bring farmer knowledge into the process from the start. This implicitly solves some of the problems of pessimism, acceptability, risk and knowledge gaps that farmers mentioned in the questionnaire and might otherwise act as impediments to the adoption of new management, including rotations, for adaptation to climate change. Discussions with farmers about the workflow, the impacts of climate change and the benefits of developing new rotations were encouraging but emphasised the challenge of how many factors can be explicitly modelled, and how much we should depend upon farmer expertise. For example, it would seem to be beneficial to make the crop models more realistic by including new crop cultivars resistant to climate change (van Etten et al. 2020) and management changes such as irrigation or intercropping (Woznicki et al. 2015, Raseduzzaman and Steen Jensen 2017, Hassen et al. 2017). However, many of these potential developments have not been well-parameterised. We propose that it would be better to be clear with farmers that the current models and the predictions of yield change are simple and based upon current cultivars and conventional management. Farmers can then examine the expected changes in crop yield with climate change and make their expert assessment of the likely impact of an introduction of new cultivars or managements for mitigation, to determine whether it might be feasible to retain a particular rotation. The change in yield predicted by the *FRE* therefore serves as an estimate of the amount of technical development necessary to retain a particular rotation. While conservative, in the sense that farmers may opt to retain crops and rotations that they know and understand, this approach of clarity with farmers may also be more pragmatic than one of trying to include all uncertainties or modelling 'realism'.

As discussed elsewhere in Volumes 63 and 64 of *Advances in Ecological Research*, many current interventions through agricultural policy, implemented in national and international regulations and accords, seek to foster crop diversity as a mechanism to support biodiversity conservation and the environment (Helfenstein et al. 2020, Kleijn et al. 2020, Vanbergen et al. 2020). In Europe, the Common Agricultural Policy, via greening measures, supports directly the spatial and temporal diversification of crops to promote the diversification of landscapes and improve ecosystem services (European Commission 2020). Rotations are a longstanding method of agricultural diversification widely used by farmers and so should be a primary target for policy interventions. In this paper we show that there is a clear link between rotational (temporal) diversity and landscape (spatial) diversity. So increasing the diversity of crops sown in rotation would enhance diversity across arable landscapes. With the availability of datasets of field-level crop use (which will be increasingly available from annual earth observation data), we can identify landscapes where temporal (or spatial) diversity is low, e.g. because of high levels of rotational synchrony or because the rotations used have low crop diversity. We would expect these types of landscapes to suffer most under future change in climate. Using the workflow in these landscapes could lead to greatest benefits for landscape diversity (and hence biodiversity and ecosystem services), and successful adaptation to future climate change.

Current agricultural conservation approaches will not meet their stated aims for biodiversity and ecosystem services within the expected timescales (Kleijn et al. 2020). Kleijn et al. (2020) argue that the key question is how to incorporate the conservation of biodiversity into farm management in a farmer-acceptable way, especially considering questions of farmer aversion to change (Chèze et al. 2020). Climate change provides this impetus for change. Climate change is an existential problem for farmers and the farming industry that has the potential to reshape agriculture (European Environment Agency 2019). It will also affect the public, and it is therefore a threat that we all share. This provides the opportunity to advance the design of agricultural landscapes that are acceptable to farmers and meet public policy aims. Rather than proposing biodiversity and ecosystem services as a primary goal of farming, the workflow facilitates farmer co-development of rotational scenarios that can then be selected for their economic and ecological performance. This does not relegate biodiversity to a place of unimportance, but rather integrates it as one of the key aspects of farmland within a relatively simple farmer-derived approach. Ultimately, we believe, this farmer-derived approach that is economically and ecologically-informed will produce acceptable workable rotational solutions to climate change adaptation and the positive transformation of agricultural landscapes.

Data

Crop sequences for England were derived from UKCEH Land Cover® Plus: Crops © and database right UKCEH, © and database right RSAC. All rights reserved. © Crown copyright and/or database right 2007. Licence number 100017572. © third party licensors.

Acknowledgements

This work is an output of the *PREAR* project (Predicting and enhancing the Resilience of European Agro-ecosystems to environmental change using crop Rotations) which was a partnership between INRAE, UKCEH, the Universities of Copenhagen and Aarhus, Solagro and Szent István University. It was funded as part of the European FACCE SURPLUS (sustainable and resilient agriculture for food and non-food systems) ERA-NET co-fund scheme of Horizon 2020 programme formed in collaboration between the European Commission and a partnership of 15 countries in the framework of the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI). The co-funding for MP and RS came from Department for Environment, Food and Rural Affairs, UK (contract SCF0313); MT, ATA and RC were funded by the Innovation Fund Denmark; ZD and MZ provided their own funds; and, DAB and SD were funded by the Agence National de la Recherche, France.

We thank Tom August (UKCEH) for support in implementing the *PREAR Future Rotations Explorer* and Alberto Martinez-de la Torre (UKCEH) for downscaling climate model outputs from the UKCP18. We are very grateful to Jørgen Brandt and Gregor Levin at the Department of Environmental Science, Aarhus University for providing us the Danish weather/climate data and crop history data, respectively. We thank Benjamin Carbonne, Luc Biju-Duval, Rémi Gounon, Claude Sarrasin and Emeline Felten for their support with the field experimentation. We thank the farmers who participated in this study, both those of the co-construction group and those responding to the questionnaire. For facilitating contact with farmers, we are indebted to Guillaume Brisset in the Hauts-de-France, France, and Jodey Peyton and Richard Pywell in the UK. We thank the GAEC MOUILLON FRERES LAURENT ET OLIVIER and Pauline Mouillon in the Bourgogne-Franche-Comté, France for their support and discussions throughout the questionnaire co-construction and interpretation process.

References

Aizen MA, Arbetman MP, Chacoff NP, et al (2020) Invasive bees and their impact on agriculture. Advances in Ecological Research 63:49–92. doi: 10.1016/bs.aecr.2020.08.001

Albizua A, Williams A, Hedlund K, Pascual U (2015) Crop rotations including ley and manure can promote ecosystem services in conventional farming systems. Applied Soil Ecology 95:54–61. doi: 10.1016/j.apsoil.2015.06.003

Aramburu Merlos F, Hijmans RJ (2020) The scale dependency of spatial crop species diversity and its relation to temporal diversity. Proceedings of the National Academy of Sciences 117:26176–26182. doi: 10.1073/pnas.2011702117

Asseng S, Ewert F, Rosenzweig C, et al (2013) Uncertainty in simulating wheat yields under climate change. Nature Climate Change 3:827–832. doi: 10.1038/nclimate1916

Austerlitz F, Smouse PE (2001) Two-Generation Analysis of Pollen Flow Across a Landscape. II. Relation Between Φft, Pollen Dispersal and Interfemale Distance. Genetics 157:851.

Bane MS, Pocock MJO, Gibert C, et al Farmer flexibility concerning future rotation planning is affected by the framing of climate predictions. doi: 10.31220/agriRxiv.2020.00025

Barbieri P, Pellerin S, Nesme T (2017) Comparing crop rotations between organic and conventional farming. Scientific Reports 7:570–10. doi: 10.1038/s41598-017-14271-6

Bennett E, et al (this issue) Ecosystem services and the resilience of agricultural landscapes

Benvenuti S (2007) Weed seed movement and dispersal strategies in the agricultural environment. Weed Biology and Management 7:141–157. doi: 10.1111/j.1445-6664.2007.00249.x

Bihaly ÁD, Hostyánszki AK, Szalai M, Sárospataki M (2020) Nesting activity of cavity-nesting bees and wasps is lower in small-scale apple orchards compared to nearby semi-natural habitats. Agr Forest Entomol 12:331. doi: 10.1111/afe.12403

Blöschl G, Hall J, Viglione A, et al (2019) Changing climate both increases and decreases European river floods. Nature 573:108–111. doi: 10.1038/s41586-019-1495-6

Bohan DA, Bohan AC, Glen DM, et al (2000) Spatial dynamics of predation by carabid beetles on slugs. J Anim Ecol 69:367–379. doi: 10.1046/j.1365-2656.2000.00399.x

Bohan DA, Boffey CWH, Brooks DR, et al (2005) Effects on weed and invertebrate abundance and diversity of herbicide management in genetically modified herbicide-tolerant winter-sown oilseed rape. Proc R Soc Biol Sci Ser B 272:463–474. doi: 10.1098/rspb.2004.3049

Bohan DA, Boursault A, Brooks DR, Petit S (2011a) National-scale regulation of the weed seedbank by carabid predators. J Appl Ecol 48:888–898. doi: 10.1111/j.1365-2664.2011.02008.x

Bohan DA, Powers SJ, Champion GT, et al (2011b) Modelling rotations: can crop sequences explain arable weed seedbank abundance? Weed Research 51:422–432. doi: 10.1111/j.1365-3180.2011.00860.x

Brooks DR, Storkey J, Clark SJ, et al (2011) Trophic links between functional groups of arable plants and beetles are stable at a national scale. J Anim Ecol 81:4–13. doi: 10.1111/j.1365-2656.2011.01897.x

Brooks DR, Bohan DA, et al (2003) Invertebrate responses to the management of genetically modified herbicide–tolerant and conventional spring crops. I. Soil-surface-active invertebrates. Philos Trans R Soc Lond Ser B Biol Sci 358:1847–1862. doi: 10.1098/rstb.2003.1407

Brown J, et al (this issue) How bioregional history could shape the future of agriculture

Bullock DG (2008) Crop rotation. Critical Reviews in Plant Sciences 11:309–326. doi: 10.1080/07352689209382349

Bürkner, P.-C. (2018). Advanced Bayesian Multilevel Modeling with the R Package brms. The R Journal 10, 395–411. doi:10.32614/RJ-2018-017.

Carbonne B, Petit S, Neidel V, et al (2020) The resilience of weed seedbank regulation by carabid beetles, at continental scales, to alternative prey. Scientific Reports 10:1–14. doi: 10.1038/s41598-020-76305-w

Carpenter B, Gelman A, Hoffman MD, et al (2017) Stan: A Probabilistic Programming Language. Journal of Statistical Software 76:1–32. doi: 10.18637/jss.v076.i01

Ceglar A, Zampieri M, Toreti A, Dentener F (2019) Observed Northward Migration of Agro-Climate Zones in Europe Will Further Accelerate Under Climate Change. Earth's Future 7:1088–1101. doi: 10.1029/2019EF001178

Champion GT, May MJ, Bennett S, et al (2003) Crop management and agronomic context of the Farm Scale Evaluations of genetically modified herbicide–tolerant crops. Philos Trans R Soc Lond Ser B Biol Sci 358:1801–1818. doi: 10.1098/rstb.2003.1405

Chan SC, Kahana R, Kendon EJ, Fowler HJ (2018) Projected changes in extreme precipitation over Scotland and Northern England using a high-resolution regional climate model. Clim Dyn 51:3559–3577. doi: 10.1007/s00382-018-4096-4

Chao A, Jost L (2012) Coverage-based rarefaction and extrapolation: standardizing samples by completeness rather than size. Ecology 93:2533–2547. doi: 10.1890/11-1952.1

Chao A, Jost L (2015) Estimating diversity and entropy profiles via discovery rates of new species. Methods in Ecology and Evolution 6:873–882. doi: 10.1111/2041-210X.12349

Chase JM, McGill BJ, McGlinn DJ, et al (2018) Embracing scale-dependence to achieve a deeper understanding of biodiversity and its change across communities. Ecol Letters 21:1737–1751. doi: 10.1111/ele.13151

Chèze B, David M, Martinet V (2020) Understanding farmers' reluctance to reduce pesticide use: A choice experiment. Ecological Economics 167:106349. doi: 10.1016/j.ecolecon.2019.06.004

Clark SJ, Rothery P, Perry JN (2005) Farm Scale Evaluations of spring-sown genetically modified herbicide-tolerant crops: a statistical assessment. Proc R Soc Biol Sci Ser B 273:237–243. doi: 10.1098/rspb.2005.3282

Clark SJ, Rothery P, Perry JN, Heard MS (2007) Farm Scale Evaluations of herbicide-tolerant crops: assessment of within-field variation and sampling methodology for arable weeds. Weed Research 47:157–163. doi: 10.1111/j.1365-3180.2007.00541.x

Colwell RK, Mao CX, Chang J (2004) interpolating, extrapolating, and comparing incidence-based species accumulation curves. Ecology 85:2717–2727. doi: 10.1890/03-0557

Cong R, Ekroos J, Smith G, Brady M (2014) What land-use pattern emerges with landscape-scale management? An ecosystem-service perspective. doi: 10.13140/2.1.2663.3601

Crist TO, Veech JA (2006) Additive partitioning of rarefaction curves and species–area relationships: unifying α-, β- and γ-diversity with sample size and habitat area. Ecol Letters 9:923–932. doi: 10.1111/j.1461-0248.2006.00941.x

Crossman ND, Bryan BA, Cooke DA (2011) An invasive plant and climate change threat index for weed risk management: Integrating habitat distribution pattern and dispersal process. Ecological Indicators 11:183–198. doi: 10.1016/j.ecolind.2008.10.011

Dauer JT, Mortensen DA, Vangessel MJ (2007) Temporal and spatial dynamics of long-distance Conyza canadensis seed dispersal. J Appl Ecol 44:105–114. doi: 10.1111/j.1365-2664.2006.01256.x

de Wit A, Boogaard H, Fumagalli D, et al (2019) 25 years of the WOFOST cropping systems model. Agricultural Systems 168:154–167. doi: 10.1016/j.agsy.2018.06.018

Duru M, Therond O, Fares M (2015a) Designing agroecological transitions; A review. Agron Sustain Dev 35:1237–1257. doi: 10.1007/s13593-015-0318-x

Duru M, Therond O, Martin G, et al (2015b) How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron Sustain Dev 35:1259–1281. doi: 10.1007/s13593-015-0306-1

Eklöf A, Jacob U, Kopp J, et al (2013) The dimensionality of ecological networks. Ecol Letters 16:577–583. doi: 10.1111/ele.12081

Engel J, Hertzog L, Tiede J, et al (2017) Pitfall trap sampling bias depends on body mass, temperature, and trap number: insights from an individual-based model. Ecosphere 8:121. doi: 10.1002/ecs2.1790

European Environment Agency (2019) Climate change adaptation in the agriculture sector in Europe. doi: 10.2800/537176

European Commission (2020) https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/greening_en

Fahrig L, Girard J, Duro D, et al (2015) Farmlands with smaller crop fields have higher within-field biodiversity. Agric Ecosyst Environ 200:219–234. doi: 10.1016/j.agee.2014.11.018

Faichnie R, et al. (this issue) Scales matter: maximising the effectiveness of interventions for pollinators and pollination

Feola G, Binder CR (2010) Towards an improved understanding of farmers' behaviour: The integrative agent-centred (IAC) framework. Ecological Economics 69:2323–2333. doi: 10.1016/j.ecolecon.2010.07.023

Feola G, Lerner AM, Jain M, et al (2015) Researching farmer behaviour in climate change adaptation and sustainable agriculture: Lessons learned from five case studies. Journal of Rural Studies 39:74–84. doi: 10.1016/j.jrurstud.2015.03.009

Firbank LG, Heard MS, Woiwod IP, et al (2003) An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. J Appl Ecol 40:2–16. doi: 10.1046/j.1365-2664.2003.00787.x

Fisher RA (1972) The Design Of Experiments. Macmillan Publishing Company.
Forster M, Bane M, Derocles S, et al (2020) FACCE SURPLUS PREAR project – Farmer questionnaire. doi: 10.5281/zenodo.4266386
Francis CA (2005) Crop Rotations. Encyclopedia of Soils in the Environment 318–322. doi: 10.1016/B0-12-348530-4/00253-8
Frei B, Guenay Y, Bohan DA, et al (2019) Molecular analysis indicates high levels of carabid weed seed consumption in cereal fields across Central Europe. J Pest Sci 92:935–942. doi: 10.1007/s10340-019-01109-5
Fuhrer J (2003) Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. Agric Ecosyst Environ 97:1–20. doi: 10.1016/S0167-8809(03)00125-7
Gaba S, Deroulers P, Bretagnolle F, Bretagnolle V (2019) Lipid content drives weed seed consumption by ground beetles (Coleoptera, Carabidae) within the smallest seeds. Weed Research 59:170–179. doi: 10.1111/wre.12354
Gaggiotti OE, Chao A, Neto PP, et al (2018) Diversity from genes to ecosystems: A unifying framework to study variation across biological metrics and scales. Evolutionary Applications 11:1176–1193. doi: 10.1111/eva.12593
Geiger F, Bengtsson J, Berendse F, et al (2010) Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Bas Appl Ecol 11:97–105. doi: 10.1016/j.baae.2009.12.001
Gendron RP (1987) Models and Mechanisms of Frequency-Dependent Predation. The American Naturalist 130:603–623. doi: 10.1086/284733
Gibbons DW, Bohan DA, Rothery P, et al (2006) Weed seed resources for birds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. Proc R Soc Biol Sci Ser B 273:1921–1928. doi: 10.1098/rspb.2006.3522
Grass I, et al. (this issue) Combining land-sparing and land-sharing in European landscapes
Gray C, Ma A, McLaughlin Ó, et al (2021) Ecological plasticity governs ecosystem services in multilayer networks. Communications Biology. doi: 10.1038/s42003-020-01547-3
Hails RS (2000) Genetically modified plants – the debate continues. Trends in Ecology & Evolution 15:14–18. doi: 10.1016/S0169-5347(99)01751-6
Hald AB (1999) The impact of changing the season in which cereals are sown on the diversity of the weed flora in rotational fields in Denmark. J Appl Ecol 36:24–32. doi: 10.1046/j.1365-2664.1999.00364.x
Halsall NB, Wratten SD (1988) The efficiency of pitfall trapping for polyphagous predatory Carabidae. Ecological Entomology 13:293–299. doi: 10.1111/j.1365-2311.1988.tb00359.x
Haan NL, et al. (this issue) Designing agricultural landscapes for arthropod-based ecosystem services in North America
Haan NL, Zhang Y, & Landis DA (2020) Predicting Landscape Configuration Effects on Agricultural Pest Suppression. Trends in Ecology & Evolution 35: 175–186. doi: 10.1016/j.tree.2019.10.003
Hassen A, Talore DG, Tesfamariam EH, et al (2017) Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: a review. Reg Environ Change 17:1713–1724. doi: 10.1007/s10113-017-1131-7
Haughton AJ, Champion GT, Hawes C, et al (2003) Invertebrate responses to the management of genetically modified herbicide–tolerant and conventional spring crops. II. Within-field epigeal and aerial arthropods. Philos Trans R Soc Lond Ser B Biol Sci 358:1863–1877. doi: 10.1098/rstb.2003.1408

Heard MS, Hawes C, et al (2003) Weeds in fields with contrasting conventional and genetically modified herbicide–tolerant crops. II. Effects on individual species. Philos Trans R Soc Lond Ser B Biol Sci 358:1833–1846. doi: 10.1098/rstb.2003.1401

Hennessy DA (2006) On Monoculture and the Structure of Crop Rotations. American Journal of Agricultural Economics 88:900–914. doi: 10.1111/j.1467-8276.2006.00905.x

Helfenstein J, Diogo V, Bürgi M, et al (2020) Conceptualizing pathways to sustainable agricultural intensification. Advances in Ecological Research 63:161–192. doi: 10.1016/bs.aecr.2020.08.005

Holland JM, Sutter L, Albrecht M, et al (2020) Moderate pollination limitation in some entomophilous crops of Europe. Agric Ecosyst Environ 302:107002. doi: 10.1016/j.agee.2020.107002

Honek A, Martinkova Z, Jarosik V (2003) Ground beetles (Carabidae) as seed predators. Eur J Entomol 100:531–544. doi: 10.14411/eje.2003.081

Honek A, Martinkova Z, Saska P, Pekar S (2007) Size and taxonomic constraints determine the seed preferences of Carabidae (Coleoptera). Bas Appl Ecol 8:343–353. doi: 10.1016/j.baae.2006.07.002

Howlett BG, et al (this issue) Using non-bee and bee pollinator - plant species interactions to design diverse plantings benefiting crop pollination services

Hurlbert SH (1971) The Nonconcept of Species Diversity: A Critique and Alternative Parameters. Ecology 52:577–586. doi: 10.2307/1934145

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 56 pages.

IPCC, 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Jarosik V (1989) Mass vs. length relationship for carabid beetles (Col., Carabidae). Pedobiologia (Jena) 33:87–90.

Jamieson S (2004) Likert scales: how to (ab)use them. Medical Education 38:1217–1218. doi: 10.1111/j.1365-2929.2004.02012.x

Jones P, Thornton P (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environmental Change 13:51–59. doi: 10.1016/S0959-3780(02)00090-0

Jost L (2007) partitioning diversity into independent alpha and beta components. Ecology 88:2427–2439. doi: 10.1890/06-1736.1

Kleijn D, Biesmeijer KJC, Klaassen RHG, et al (2020) Integrating biodiversity conservation in wider landscape management: Necessity, implementation and evaluation. Advances in Ecological Research 63:127–159. doi: 10.1016/bs.aecr.2020.08.004

Kondoh M (2003) Foraging Adaptation and the Relationship Between Food-Web Complexity and Stability. Science 299:1388–1391. doi: 10.1126/science.1079154

Kremen C (2020) Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. Emerging Topics in Life Sciences 4:229–240. doi: 10.1042/ETLS20190205

Land M, Haddaway NR, Hedlund K, et al (2017) How do selected crop rotations affect soil organic carbon in boreo-temperate systems? A systematic review protocol. Environ Evid 6:1–8. doi: 10.1186/s13750-017-0086-y

Levavasseur F, Martin P, Bouty C, et al (2016) RPG Explorer: A new tool to ease the analysis of agricultural landscape dynamics with the Land Parcel Identification System. Computers and Electronics in Agriculture 127:541–552. doi: 10.1016/j.compag.2016.07.015

Leenhardt D, Angevin F, Biarnès A, et al (2010) Describing and locating cropping systems on a regional scale. A review. Agron Sustain Dev 30:131–138. doi: 10.1051/agro/2009002

Leng G, Huang M (2017) Crop yield response to climate change varies with crop spatial distribution pattern. Scientific Reports 7:1–10. doi: 10.1038/s41598-017-01599-2

Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. Nature 529:84–87. doi: 10.1038/nature16467

Luff, M. L. (2007). The Carabidae (Ground Beetles) of Britain and Ireland. St Albans, UK: Royal Entomological Society.

Ma A, Lu X, Gray C, et al (2018) Ecological networks reveal resilience of agro-ecosystems to changes in farming management. Nature Ecology & Evolution 2018 3:260–264. doi: 10.1038/s41559-018-0757-2

MacLaren C, Storkey J, Menegat A, et al (2020) An ecological future for weed science to sustain crop production and the environment. A review. Agron Sustain Dev 40:39–29. doi: 10.1007/s13593-020-00631-6

Mahaut L, Gaba S, Fried G (2019) A functional diversity approach of crop sequences reveals that weed diversity and abundance show different responses to environmental variability. J Appl Ecol 56:1400–1409. doi: 10.1111/1365-2664.13389

Mahé I, Cordeau S, Bohan DA, et al (2020) Soil seedbank: Old methods for new challenges in agroecology? Ann App Biol 69:497. doi: 10.1111/aab.12619

Mancini F, Woodcock BA, Redhead J, et al (2020) Detecting landscape scale consequences of insecticide use on invertebrate communities. Advances in Ecological Research 63:93–126. doi: 10.1016/bs.aecr.2020.07.001

Manly BFJ, Miller P, Cook LM (1972) Analysis of a Selective Predation Experiment. The American Naturalist 106:719–736. doi: 10.1086/282808

Marrec R, Caro G, Miguet P, et al (2017) Spatiotemporal dynamics of the agricultural landscape mosaic drives distribution and abundance of dominant carabid beetles. Landscape Ecol 32:2383–2398. doi: 10.1007/s10980-017-0576-x

Marshall EJP, Brown VK, Boatman ND, et al (2003) The role of weeds in supporting biological diversity within crop fields. Weed Research 43:77–89. doi: 10.1046/j.1365-3180.2003.00326.x

McGlinn DJ, Xiao X, May F, et al (2019) Measurement of Biodiversity (MoB): A method to separate the scale-dependent effects of species abundance distribution, density, and aggregation on diversity change. Methods in Ecology and Evolution 10:258–269. doi: 10.1111/2041-210X.13102

Melander B, Munier-Jolain N, Charles R, et al (2017) European Perspectives on the Adoption of Nonchemical Weed Management in Reduced-Tillage Systems for Arable Crops. Weed technol 27:231–240. doi: 10.1614/WT-D-12-00066.1

Mendelsohn R, Nordhaus WD, Shaw D, (1994) The impact of global warming on agriculture: a ricardian analysis. The American Economic Review, 753–771.

Merkle EC, Fitzsimmons E, Uanhoro J, Goodrich B (2020) Efficient Bayesian Structural Equation Modeling in Stan. https://arxiv.org/abs/2008.07733v1

Merkle EC, Furr D, Rabe-Hesketh S (2018) Bayesian comparison of latent variable models: Conditional vs marginal likelihoods. Psychometrika 84:802–829.Mgendi G, Shiping M, Xiang C (2019) A Review of Agricultural Technology Transfer in Africa: Lessons from Japan and China Case Projects in Tanzania and Kenya. Sustainability 11:6598. doi: 10.3390/su11236598

Möhring N, Dalhaus T, Enjolras G, Finger R (2020) Crop insurance and pesticide use in European agriculture. Agricultural Systems 184:102902. doi: 10.1016/j.agsy.2020.102902

Moorcroft D, Whittingham MJ, Bradbury RB, Wilson JD (2002) The selection of stubble fields by wintering granivorous birds reflects vegetation cover and food abundance. J Appl Ecol 39:535–547. doi: 10.1046/j.1365-2664.2002.00730.x

Morgounov A, Sonder K, Abugalieva A, et al (2018) Effect of climate change on spring wheat yields in North America and Eurasia in 1981-2015 and implications for breeding. PLoS ONE 13:e0204932. doi: 10.1371/journal.pone.0204932

Mulder C, Sechi V, Woodward G, Bohan DA (2017) Ecological Networks in Managed Ecosystems: Connecting Structure to Services. In: Adaptive Food Webs: Stability and Transitions of Real and Model Ecosystems, 1st edn. Cambridge University Press, pp 214–227

Opdam P (2020) Implementing human health as a landscape service in collaborative landscape approaches. Landscape and Urban Planning 199:103819. doi: 10.1016/j.landurbplan.2020.103819

Ouin A, et al. (this issue) Building a shared vision of the future for multifunctional agricultural landscapes - Lessons from a Long Term Socio-Ecological Research site in south-western France.

Pankhurst CE, Lynch JM (2005) Biocontrol of soil-borne plant diseases. Encyclopedia of Soils in the Environment 129–136. doi: 10.1016/B0-12-348530-4/00137-5

Pannell DJ, Stewart V, Bennett A, et al (2004) RIM: a bioeconomic model for integrated weed management of Lolium rigidum in Western Australia. Agricultural Systems 79:305–325. doi: 10.1016/S0308-521X(03)00089-1

Paradis E, Baillie SR, Sutherland WJ (2002) Modeling large-scale dispersal distances. Ecol Model 151:279–292. doi: 10.1016/S0304-3800(01)00487-2

Perry JN, Rothery P, Clark SJ, et al (2003) Design, analysis and statistical power of the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. J Appl Ecol 40:17–31. doi: 10.1046/j.1365-2664.2003.00786.x

Petit S, Boursault A, Bohan DA (2014) Weed seed choice by carabid beetles (Coleoptera: Carabidae): Linking field measurements with laboratory diet assessments. Eur J Entomol 111:615–620. doi: 10.14411/eje.2014.086

Petit S, Cordeau S, Chauvel B, et al (2018) Biodiversity-based options for arable weed management. A review. Agron Sustain Dev 38:1–21. doi: 10.1007/s13593-018-0525-3

Petit S, Muneret L, Carbonne B, et al (2020) Landscape-scale expansion of agroecology to enhance natural pest control: A systematic review. Advances in Ecological Research 63:1–48. doi: 10.1016/bs.aecr.2020.09.001

Pocock MJO, Evans DM, Memmott J (2012) The Robustness and Restoration of a Network of Ecological Networks. Science 335:973–977. doi: 10.1126/science.1214915

Pocock MJO, Schmucki R, Bohan DA (2020) Inferring species interactions from ecological survey data: a mechanistic approach to predict quantitative food webs of seed-feeding by carabid beetles. bioRxiv 33:2020.11.09.375402. doi: 10.1101/2020.11.09.375402

Poggi S, et al. (this issue) How can models foster the transition towards future agricultural landscapes?

Pyke GH, Pulliam HR, Charnov EL (1977) Optimal Foraging: A Selective Review of Theory and Tests. The Quarterly Review of Biology 52:137–154. doi: 10.1086/409852

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Raseduzzaman M, Steen Jensen E (2017) Does intercropping enhance yield stability in arable crop production? A meta-analysis. European Journal of Agronomy 91:25–33. doi: 10.1016/j.eja.2017.09.009

Ritchie PDL, Harper AB, Smith GS, et al (2019) Large changes in Great Britain's vegetation and agricultural land-use predicted under unmitigated climate change. Environ Res Lett 14:114012. doi: 10.1088/1748-9326/ab492b

Rizzo D, Therond O, Lardy R, et al (2019) A rapid, spatially explicit approach to describe cropping systems dynamics at the regional scale. Agricultural Systems 173:491–503. doi: 10.1016/j.agsy.2019.04.003

Robinson RA, Sutherland WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. J Appl Ecol 39:157–176. doi: 10.1046/j.1365-2664.2002.00695.x

Rosseel Y (2012) lavaan: An R Package for Structural Equation Modeling. Journal of Statistical Software 48:1–36. doi: 10.18637/jss.v048.i02

Roubinet E, Jonsson T, Malsher G, et al (2018) High Redundancy as well as Complementary Prey Choice Characterize Generalist Predator Food Webs in Agroecosystems. Scientific Reports 8:689–10. doi: 10.1038/s41598-018-26191-0

Saska P, Honek A, Martinkova Z (2019) Preferences of carabid beetles (Coleoptera: Carabidae) for herbaceous seeds. Acta Zool Acad Sci H 65:57–76. doi: 10.17109/AZH.65.Suppl.57.2019

Sebastián-González E, Pires MM, Donatti CI, et al (2017) Species traits and interaction rules shape a species-rich seed-dispersal interaction network. Ecol Evol 7:4496–4506. doi: 10.1002/ece3.2865

Schellhorn NA, Gagic V, Bommarco R (2015) Time will tell: resource continuity bolsters ecosystem services. Trends in Ecology & Evolution 30:524–530. doi: 10.1016/j.tree.2015.06.007

Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences 106:15594–15598. doi: 10.1073/pnas.0906865106

Schmucki R, Bohan DA, Pocock MJO (2020) Combined effect of crop rotation and carabid beetles on weed dynamics in arable fields. bioRxiv 2020.12.04.411918. doi: 10.1101/2020.12.04.411918

Schüpbach B, Weiß SB, Jeanneret P, et al (2021) What determines preferences for semi-natural habitats in agrarian landscapes? A choice-modelling approach across two countries using attributes characterising vegetation. Landscape and Urban Planning 206:103954. doi: 10.1016/j.landurbplan.2020.103954

Scott RJ, Baker P, Bell D, et al (2012a) Farm scale evaluations of herbicide tolerant genetically modified crops—Beet. NERC Environmental Information Data Centre. doi: 10.5285/86cd1a60-64f1-4087-a9f1-a3d8a9f8f535

Scott RJ, Baker P, Bell D, et al (2012b) Farm scale evaluations of herbicide tolerant genetically modified crops—Maize. NERC Environmental Information Data Centre. doi: 10.5285/ca6752ed-3a22-4790-a86d-afadaedda082

Scott RJ, Baker P, Bell D, et al (2012c) Farm scale evaluations of herbicide tolerant genetically modified crops—Spring oilseed rape. NERC Environmental Information Data Centre. doi: 10.5285/0023bd6e-4dd7-462c-aacf-f13083b054ab

Scott RJ, Baker P, Bell D, et al (2012d) Farm scale evaluations of herbicide tolerant genetically modified crops—Winter oilseed rape. NERC Environmental Information Data Centre. doi: 10.5285/37a503da-d75c-4d72-8e8b-b11c2fdc7d92

Sint D, Guenay Y, Mayer R, et al (2018) The effect of plant identity and mixed feeding on the detection of seed DNA in regurgitates of carabid beetles. Ecol Evol 8:10834–10846. doi: 10.1002/ece3.4536

Skamarock WC, Klemp JB, Dudhia J, et al (2008). A description of the advanced research WRF version 3. NCAR Technical note-475+ STR. pp. 113.

Skrimizea E, Lecuyer L, Bunnefeld N, et al (2020) Sustainable agriculture: Recognizing the potential of conflict as a positive driver for transformative change. Advances in Ecological Research 63:255–311. doi: 10.1016/bs.aecr.2020.08.003

Sloat LL, Davis SJ, Gerber JS, et al (2020) Climate adaptation by crop migration. Nat Comms 11:1–9. doi: 10.1038/s41467-020-15076-4

Smid SC, McNeish D, Miočević M, van de Schoot R (2019) Bayesian Versus Frequentist Estimation for Structural Equation Models in Small Sample Contexts: A Systematic Review. Structural Equation Modeling: A Multidisciplinary Journal 27:131–161. doi: 10.1080/10705511.2019.1577140

Smith V, Bohan DA, Clark SJ, et al (2008) Weed and invertebrate community compositions in arable farmland. Arthropod-Plant Interactions 2:21–30. doi: 10.1007/s11829-007-9027-y

Smith RG, Mortensen DA, Ryan MR (2010) A new hypothesis for the functional role of diversity in mediating resource pools and weed–crop competition in agroecosystems. Weed Research 50:37–48. doi: 10.1111/j.1365-3180.2009.00745.x

Spence A, Pidgeon N (2010) Framing and communicating climate change: The effects of distance and outcome frame manipulations. Global Environmental Change 20:656–667. doi: 10.1016/j.gloenvcha.2010.07.002

Staudacher K, Rubbmark OR, Birkhofer K, et al (2018) Habitat heterogeneity induces rapid changes in the feeding behaviour of generalist arthropod predators. Funct Ecol 32:809–819. doi: 10.1111/1365-2435.13028

Stein S, Steinmann H-H (2018) Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – A case study from Central Europe. European Journal of Agronomy 92:30–40. doi: 10.1016/j.eja.2017.09.010

Stephens DW, Lynch JF, Sorensen AE, Gordon C (1986) Preference and Profitability: Theory and Experiment. The American Naturalist 127:533–553. doi: 10.1086/284501

Storkey J, Bruce TJA, McMillan VE, Neve P (2019) The Future of Sustainable Crop Protection Relies on Increased Diversity of Cropping Systems and Landscapes. In: Agroecosystem Diversity. Academic Press, pp 199–209

Storkey J, Neve P (2018) What good is weed diversity? Weed Research 58:239–243. doi: 10.1111/wre.12310

Tamburini G, Bommarco R, Wanger TC, et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6:eaba1715. doi: 10.1126/sciadv.aba1715

Teixeira EI, de Ruiter J, Ausseil A-G, et al (2018) Adapting crop rotations to climate change in regional impact modelling assessments. Science of The Total Environment 616-617:785–795. doi: 10.1016/j.scitotenv.2017.10.247

Therond O, Duru M, Roger-Estrade J, Richard G (2017) A new analytical framework of farming system and agriculture model diversities. A review. Agron Sustain Dev 37:1–24. doi: 10.1007/s13593-017-0429-7

Thomas CFG, Brown NJ, Kendall DA (2006) Carabid movement and vegetation density: Implications for interpreting pitfall trap data from split-field trials. Agric Ecosyst Environ 113:51–61. doi: 10.1016/j.agee.2005.08.033

Tigchelaar M, Battisti DS, Naylor RL, Ray DK (2018) Future warming increases probability of globally synchronized maize production shocks. Proceedings of the National Academy of Sciences 115:6644–6649. doi: 10.1073/pnas.1718031115

Tinbergen L (1960) The Natural Control of Insects in Pinewoods. Arch Néerl Zool 13:265–343. doi: 10.1163/036551660X00053

Trichard A, Alignier A, Biju-Duval L, Petit S (2013) The relative effects of local management and landscape context on weed seed predation and carabid functional groups. Bas Appl Ecol 14:235–245. doi: 10.1016/j.baae.2013.02.002

Vanbergen AJ, Aizen MA, Cordeau S, et al (2020) Transformation of agricultural landscapes in the Anthropocene: Nature's contributions to people, agriculture and food security. Advances in Ecological Research 63:193–253. doi: 10.1016/bs.aecr.2020.08.002

van Erp S, Mulder J, Oberski DL (2018) Prior sensitivity analysis in default Bayesian structural equation modeling. Psychological Methods 23:363–388. doi: 10.1037/met0000162

van Etten J, de Sousa K, Aguilar A, et al (2019) Crop variety management for climate adaptation supported by citizen science. Proceedings of the National Academy of Sciences 116:4194–4199. doi: 10.1073/pnas.1813720116

Vasileiadis VP, Sattin M, Otto S, et al (2011) Crop protection in European maize-based cropping systems: Current practices and recommendations for innovative Integrated Pest Management. Agricultural Systems 104:533–540. doi: 10.1016/j.agsy.2011.04.002

Vialatte A, Barnaud C, Blanco J, et al (2019) A conceptual framework for the governance of multiple ecosystem services in agricultural landscapes. Landscape Ecol 34:1653–1673. doi: 10.1007/s10980-019-00829-4

Vogel E, Donat MG, Alexander LV, et al (2019) The effects of climate extremes on global agricultural yields. Environ Res Lett 14:054010. doi: 10.1088/1748-9326/ab154b

Wallinger C, Sint D, Baier F, et al (2015) Detection of seed DNA in regurgitates of granivorous carabid beetles. Bull Entomol Res 105:728–735. doi: 10.1017/S000748531500067X

Watkinson AR, Freckleton RP, Robinson RA, et al (2000) Predictions of Biodiversity Response to Genetically Modified Herbicide-Tolerant Crops. Science 289:1554–1557. doi: 10.1126/science.289.5484.1554

Westerman PR, Dixon PM, Liebman M (2009) Burial rates of surrogate seeds in arable fields. Weed Research 49:142–152. doi: 10.1111/j.1365-3180.2008.00684.x

Weisberger D, Nichols V, Liebman M (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. PLoS ONE 14:e0219847. doi: 10.1371/journal.pone.0219847

Wilson JD, Morris AJ, Arroyo BE, et al (1999) A review of the abundance and diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to agricultural change. Agric Ecosyst Environ 75:13–30. doi: 10.1016/S0167-8809(99)00064-X

Wilson S, Mitchell GW, Pasher J, et al (2017) Influence of crop type, heterogeneity and woody structure on avian biodiversity in agricultural landscapes. Ecological Indicators 83:218–226. doi: 10.1016/j.ecolind.2017.07.059

Winder L, Alexander CJ, Holland JM, et al (2005) Predatory activity and spatial pattern: the response of generalist carabids to their aphid prey. J Anim Ecol 74:443–454. doi: 10.1111/j.1365-2656.2005.00939.x

Wolf. J, 2011. Climate Change Adaptation in Developed Nations: From Theory to Practice, Advances in Global Change Research. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-007-0567-8

Woznicki SA, Nejadhashemi AP, Parsinejad M (2015) Climate change and irrigation demand: Uncertainty and adaptation. Journal of Hydrology: Regional Studies 3:247–264. doi: 10.1016/j.ejrh.2014.12.003

Yates F (1964) Sir Ronald Fisher and the Design of Experiments. Biometrics 20:307. doi: 10.2307/2528399

Young JC, Rose DC, Mumby HS, et al (2018) A methodological guide to using and reporting on interviews in conservation science research. Methods in Ecology and Evolution 9:10–19. doi: 10.1111/2041-210X.12828

Zhang X, Cai X (2011) Climate change impacts on global agricultural land availability. Environ Res Lett 6:014014. doi: 10.1088/1748-9326/6/1/014014

Zohry A, Ouda S (2018) Crop Rotation Defeats Pests and Weeds. In: Crop Rotation. Springer, Cham, Cham, pp 77–88