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TOPICAL REVIEW

Meta-analysis of climate impacts and uncertainty on crop yields in Europe

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Abstract

Future changes in temperature, rainfall and soil moisture could threaten agricultural land use and crop productivity in Europe, with major consequences for food security. We assessed the projected impacts of climate change on the yield of seven major crop types (*viz* wheat, barley, maize, potato, sugar beet, rice and rye) grown in Europe using a systematic review (SR) and meta-analysis of data reported in 41 original publications from an initial screening of 1748 studies. Our approach adopted an established SR procedure developed by the Centre for Evidence Based Conservation constrained by inclusion criteria and defined methods for literature searches, data extraction, meta-analysis and synthesis. Whilst similar studies exist to assess climate impacts on crop yield in Africa and South Asia, surprisingly, no comparable synthesis has been undertaken for Europe. Based on the reported results ($n = 729$) we show that the projected change in average yield in Europe for the seven crops by the 2050s is +8%. For wheat and sugar beet, average yield changes of +14% and +15% are projected, respectively. There were strong regional differences with crop impacts in northern Europe being higher (+14%) and more variable compared to central (+6%) and southern (+5) Europe. Maize is projected to suffer the largest negative mean change in southern Europe (−11%). Evidence of climate impacts on yield was extensive for wheat, maize, sugar beet and potato, but very limited for barley, rice and rye. The implications for supporting climate adaptation policy and informing climate impacts crop science research in Europe are discussed.

Introduction

European agriculture supports a relatively small proportion (4.7%) of the total working population, but is responsible for managing nearly half of the EU's land area (EEA 2015). It therefore plays a critical role in influencing the landscape and the quality of the natural environment. Global warming and a changing climate are expected to have a multitude of direct and indirect impacts, including: modifying the composition of land use and land suitability for food and fibre crops; shifting growing periods; and influencing crop yield and resource use efficiencies, including water and energy demand (Olesen and Bindi 2002, Daccache *et al* 2015). These climate-related risks raise important concerns regarding the future sustainability and resilience of certain crops in Europe, since agriculture plays a multifunctional role in integrating natural resources management, rural development and food production and underpinning environmental heritage through the maintenance of semi-natural habitats, landscape and biodiversity (EUROSTAT 2014). Agriculture also supports the economy for rural communities especially in the southern Mediterranean, central and eastern European regions where it buffers rural poverty (Davidova *et al* 2010, Fritsch *et al* 2010) and enhances the social fabric of rural areas by contributing to more balanced rural land development. Climate change therefore threatens to impact significantly on both the production of food crops and the rural livelihoods which depend on them.

Europe is considered to be one of the most productive suppliers of food and fibre (Olesen *et al* 2011) contributing over half of global trade in food products

(Iglesias *et al* 2011). For example, in 2008 Europe accounted for a fifth of global meat and cereal production. The levels of productivity of European agriculture are also high, notably in Western Europe, where average cereal yields are reported to be 60% higher than the world average (Olesen *et al* 2011). However, a changing climate will result in differing impacts (both positive and negative) across Europe depending on local soils and agroclimatic variation, the composition and intensity of agricultural land use, the availability of irrigation infrastructure to offset drought risks, as well as the prevailing political and agro-economic policy environments. How these underlying conditions vary from one region to another across Europe is expected to strongly impact the responsiveness and adaptive capacity of agricultural systems to climate change (Trnka *et al* 2011). Generally, more wide ranging negative effects are expected in the economically less developed areas due to their low adaptive capacity (Field 2012). Negative effects are also expected to be more acute in southern Europe where increased water shortages and extreme weather events are projected to reduce crop yields, lead to greater yield variability and a reduction in the areas suitable for cropping (Olesen and Bindi 2002). There are also expected to be significant increases in the demand for irrigation water and energy for pumping (Rodríguez-Díaz *et al* 2011, Daccache *et al* 2015). Conversely, in northern Europe, climate change could have positive impacts on agriculture through elevated temperatures and CO_2 concentrations increasing crop productivity, although there could be increased risks from flooding (Bronstert 2003) and a greater reliance on supplemental irrigation to cope with changes in land suitability, particularly for high-value vegetable cropping (Daccache *et al* 2012).

Whilst many published studies have investigated the impacts of climate change on individual crop types and agricultural systems in Europe, the often confounding reported effects and large magnitudes of impact make developing robust policies for supporting climate change adaptation very challenging. Given concerns regarding food security and the vulnerability of European agriculture to climate variability (Reidsma *et al* 2010), the objective of this paper was to review and assess the projected impacts of climate change on crop yields in Europe using a systematic review (SR) of published scientific and grey literature. SRs are increasingly being used in support of evidence-based approaches to formulate policy by providing unbiased and robust syntheses of scientific evidence. Whilst similar studies exist to assess climate impacts on crop yield in Africa and South Asia (Roudier *et al* 2011, Knox *et al* 2012), surprisingly, no such comparable synthesis has been undertaken for Europe. The study findings aim to provide new information to support the development of appropriate farmer adaptation responses for crop production in Europe (Olesen *et al* 2011), to inform future crop modelling research (Ewert 2012) and to provide new insights for climate adaptation policy.

Methods

Our approach adopted an established SR procedure developed by the Centre for Evidence Based Conservation (CEBC) constrained by inclusion criteria and defined methods for literature searches, data extraction, meta-analysis and synthesis (Centre for Evidence-Based Conservation 2010). The aim of the SR was to assess the projected impacts of climate change on the yield of seven important crops (*viz* wheat, barley, maize, potato, sugar beet, rice and rye) which are grown extensively across Europe. We included both biophysically based crop modelling studies and statistical studies using GCM climate projections from different time horizons in the SR. We excluded those studies that dealt with the effects of extreme events, such as droughts or floods, on crop responses, and those that considered 'food production' activities since these are affected by other non-biophysical factors. A detailed description of the protocol used to establish the methods for data extraction, development of the meta-database and data synthesis are included in the supplementary information. The SR approach used here for Europe was similar to that described by Knox *et al* (2012) for Africa and Asia.

Following CEBC convention, the research question was broken down into four PICO components, namely (i) the population (agricultural food crops in Europe), (ii) interventions (projected climate changes based on global circulation models and a time horizon up to the 2080s; temperature, rainfall and CO_2 concentration were considered as the main climate drivers), (iii) comparators (changes relative to a baseline, defined as 1961–1990, although more recent studies have started using a later baseline), and (iv) outcomes (defined as changes in forecast average yield or variation in yield). Unique PICO keywords were defined together with a list of relevant bibliographic databases covering both the scientific literature (ISI Web of Science™, Scopus™, ScienceDirect™, Ingenta Connect™) and other sources (e.g. EBSCO GreenFILE, CSA Natural Sciences, FAO Repository). A set of search terms was defined and trialled using Web of Science™, in order to assess the suitability of specific keywords and search strings. The chosen search term was then applied to each bibliographic database. Academic bibliographic sources were sampled first. For the website searches, the same search string was used and the first 50 hits reviewed. Following removal of duplicates, all the references retrieved were then collated in Mendeley™, an open source bibliographic management software package. The published dates for literature included in the review were a vital feature as GCMs and emissions scenario have been regularly updated. In this SR, any literature that was either a

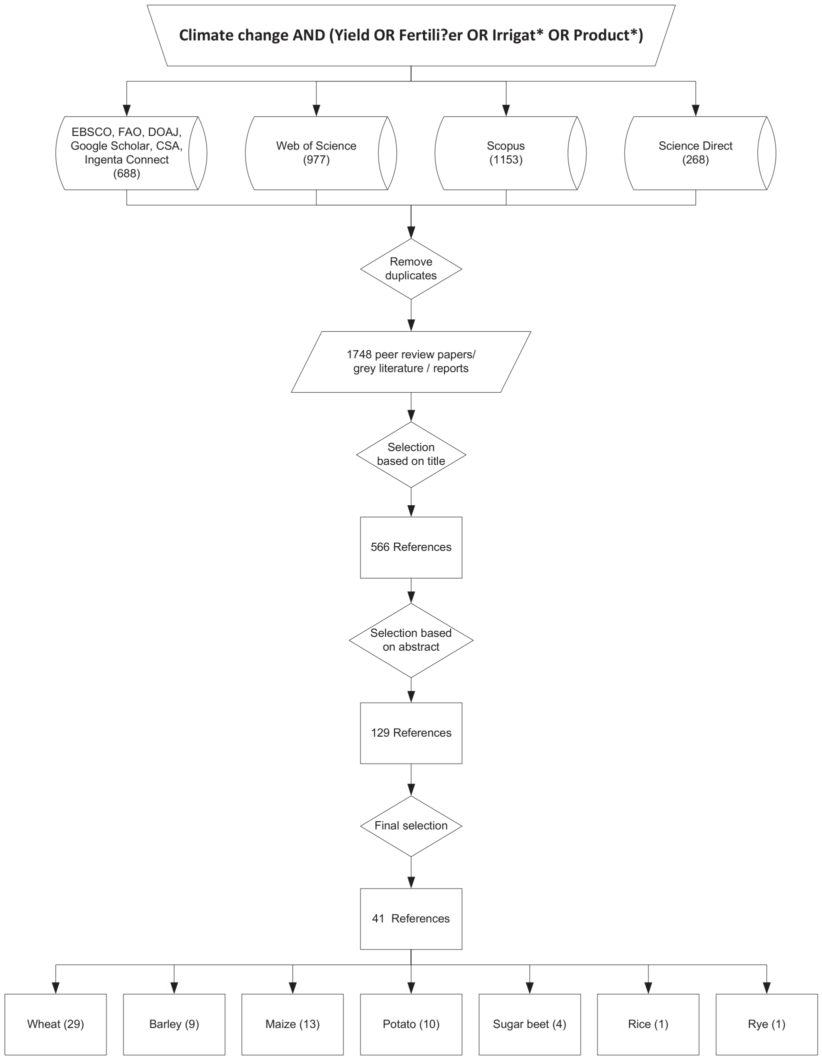

Figure 1. Schematic representation of the systematic review process.

product of the 3rd IPCC Assessment Report (IPCC 2001a, 2001b) or any earlier reports were considered outdated and thus excluded.

The inclusion criteria used to screen the literature for relevance included (i) relevant subjects (crops defined above; field to regional scales; any countries or regions within Europe; small-scale and commercial/industrial agriculture), (ii) types of intervention (IPCC climate change scenario; a time horizon up to the 2080s; projected changes in mean, total or seasonal climate), (iii) comparators (future yield values compared to present/baseline values), (iv) methods (controlled experiments and biophysical modelling studies), and (v) outcomes (studies that considered changes in crop suitability, performance, variability and/or sustainability). The first filtering was based on the source title; a second filter was then applied based on the source abstract. Full documents (peer review articles, industry reports) were only reviewed after satisfying all inclusion criteria. The screening was undertaken by two researchers working independently to ensure consistency in the process.

A schematic representation of the screening process is given in figure 1. We ultimately identified and screened 1748 sources of literature, of which 41 were subsequently selected and analysed, to provide 729 ‘observations’ of projected yield variation by crop and region, relative to a historical baseline. All relevant data were extracted and combined in a meta-database. Due to the disparity in the methods used for yield estimation and limited reporting on yield variability, it was not possible to use a weighted meta-analysis, as commonly applied in conventional SRs of experimental results. Hence, the mean forecast yield variations were compared with a zero response using a Student’s t-test on the full dataset and afterwards repeated for a number of subsets aggregated by geographical region (northern, central and southern Europe), by climate GCM model, time slice, crop type and crop modelling approach (complex biophysical or

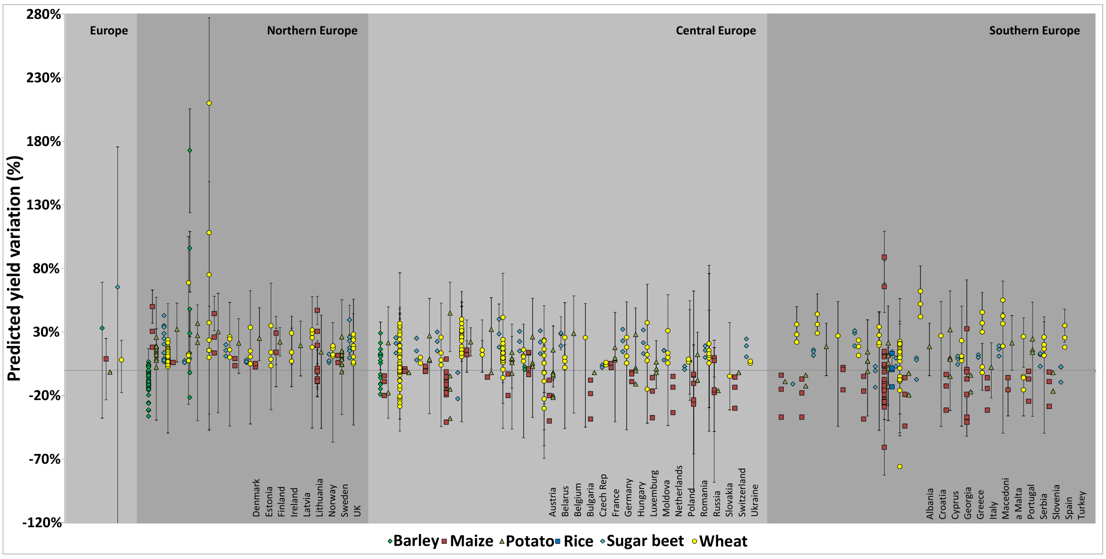

Figure 2. Variation in projected change in average yield (%) for all observations in Europe.

Table 1. Summary of reported impacts of projected change (%) in average yield for all crops and split into northern (NE), central (CE) and southern (SE) Europe.

Crop	*n*	Mean variation %	Crops with significant variation	*n*	Mean variation %	Crops with non-significant variation	*n*
All crops	729	+8	Wheat	293	+14	Barley	69
			Maize	149	−6	Rice	4
			Potato	109	+8	Rye	2
			Sugar beet	103	+15		
Northern Europe (NE)	224	+14	Wheat	89	+18	Barley	49
			Maize	24	+14	Rye	2
			Potato	31	+17		
			Sugar beet	29	+17		
Central Europe (CE)	312	+6	Wheat	140	+10	Barley	19
			Maize	64	−9		
			Potato	47	+5		
			Sugar beet	42	+17		
Southern Europe (SE)	188	+5	Wheat	63	+18	Potato	30
			Maize	60	−11	Rice	4
			Sugar beet	31	+8		

Note: Refer to supplementary information for countries included in each region; n = number of observed mean yield variations. This could include some from the same source for different time slices and/or countries; level of significance tested ($p < 0.05$) by comparing the confidence interval of the mean with zero; in each region and time slice, data was not necessarily available for all crops e.g. rice and rye.

simple statistical). The results included all reported yield forecasts, for all time slices, for all GCM combinations (whether single or ensemble) and for all crop modelling approaches (whether based on simple statistical trends or more complex biophysical modelling). We therefore conducted further statistical analyses to differentiate subsets from the meta-database (by time slice, climate model and crop modelling approach) to highlight which factors contributed most to the projected change in average yield in order to analyse the uncertainty. The countries included in each region are listed in the supplementary information.

Results and discussion

Regional climate impacts

The projected impacts of climate change on yield by crop type, for Europe as a whole and aggregated into sub-regions (northern, central and southern) are shown in figure 2. The data shown correspond to the forecast yield variations for each crop, for all GCM models, all time slices and all crop models. The whiskers represent the minimum and maximum reported yield variation, where published. Table 1 summarises the primary data and shows that for Europe as a whole, most studies project a positive impact on crop yield. The reported increases being largely due to rising atmospheric CO_2 concentrations, enhancing both crop productivity and resource use efficiency. Overall, a projected change in average yield of +8% was identified, but with large differences between both individual crops (for example, wheat +14%; maize −6%) and regions (northern Europe +14%; southern Europe +5%). Crops with the most observations and a statistically significant yield variation were wheat, maize, potato and sugar beet. Conversely, data for barley, rice and rye were much less extensive, so projected variations in average yield were not statistically significant.

When the data were disaggregated by time horizon, only changes in wheat and sugar beet yield were statistically significant. However, it is important to note that there were no data available on forecast yields for all crops in all regions in all time horizons, so lack of a significant response may in part be due to the absence, or limited number of studies for certain crops and/or regions.

For northern Europe, most evidence related to wheat ($n = 89$) with observations available from studies conducted in almost all countries in the region. In contrast, there was very limited published data on rye ($n = 2$) and none for rice. The evidence projected higher yield increases both on average and across all crop types and countries, although the variability in reported impacts was also surprisingly high (figure 2). Significant average yield changes were identified for maize and potato (+14% and +17%, respectively), with particularly strong increases in the 2050s (+12% and +18%) and 2080s (+19% and +14%). The average yield change for barley (−1%) was not statistically significant.

For central Europe, the average yield change was +6%, which was relatively constant through the different time horizons and for all crops. Wheat accounted for the largest number of observations ($n = 140$) with a moderate projected yield increase towards the end of the century (+7% for the 2020s rising to +11% by the 2080s). Sugar beet showed a steady increase in projected average yield through time. However, it is important to recognise the decrease in projected change in average yield for maize from −9% for the 2020s down to −15% by the 2080s. The projected changes in yield in central Europe were broadly consistent with those for northern Europe, showing positive impacts for most crops apart from maize.

Climate impacts for southern Europe also showed an increase in average yield although the data for the 2080s was not statistically significant. Wheat showed a consistent, significant increase in projected average yield (+18%), in contrast to maize which showed a sharp decrease, particularly by the 2080s (−28%). Reported data for potato showed a significant increase in projected average yield for the 2020s and the 2050s (+11% and +10%, respectively). However, by the 2080s the trend reverses, with a significant projected change in average yield of −10%. These data were drawn from a single study covering the European region using a crop modelling methodology and climate data, generating single climate impacts for potato for each country separately. The frequency distribution of the projected change in average yield for all crops, disaggregated into European regions, is shown in figure 3. This shows that most of the observations lie between the −5% and +15% bins.

For many of the crops studied, notably cereals and sugar beet, Europe is a significant contributor to global production. For example, in 2014, the harvested production of cereals (including rice) in the EU-28 was estimated to be 334 million tonnes, representing 13% of global cereal production (FAOSTAT 1998). Whilst globally most sugar is derived from sugarcane, beet production in the EU-28 still provides 20% of global sugar demand and constitutes half of global production (EUROSTAT 2014). Given a rising global population, reducing the amount of food produced in Europe is not a viable option. Positive or negative changes in yield in Europe will not only influence future levels of self-sufficiency but could also have serious indirect impacts on international agricultural trade, food supply-chains and commodity markets. To inform robust decision-making regarding policies for climate adaptation, it is therefore important to set the projected climate impacts on food crops in Europe as reported in this study against equivalent projected yield changes internationally. For wheat, the mean projected climate impact in Europe (+14%) contrast sharply with previous research by Knox *et al* (2012) who reported significant a reduction in Africa (−17.2%). For maize, a projected mean yield reduction of −6% in Europe was similar to Africa (−5.4%) but much less than S Asia (−15.9%). For other important crops in Europe including sugar beet (+15%) and potatoes (+8%) there are no equivalent reported data for Africa or S Asia. For rice, evidence from studies in Europe, Africa and S Asia were all insufficient to deduce any significant yield variation, highlighting the pressing need for further research to expand the evidence base. For sugarcane, a lack of evidence on climate yield impacts in Africa should also be addressed given the recent focus on sugarcane expansion as a means to power agricultural transformation and economic development in Africa (Hess *et al* 2016). The findings from this research corroborate other studies that show how crop productivity impacts in higher-latitude temperate regions, such as northern Europe, are generally expected to be less severe than in lower-latitude more tropical regions (Challinor *et al* 2014). These wide geospatial variations in climate impact confirm an enhanced role for trade with increased flows in agricultural commodities from the mid to high latitude regions to low latitude regions needed to offset the more extreme climate impacts, where both production and export potential could be severely hampered (Elbehri *et al* 2015).

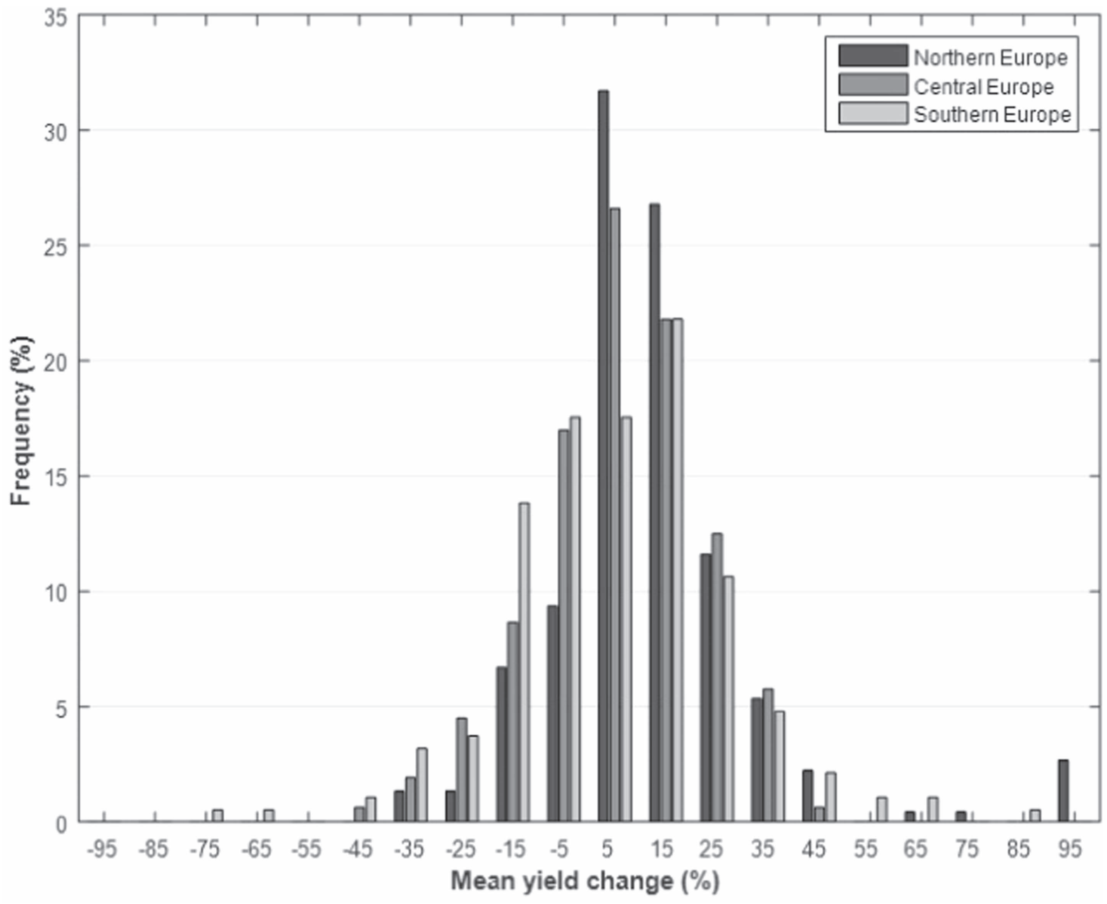

Figure 3. Frequency distribution of projected change in average yield (%) for all observations ($n = 729$) by region (northern, central and southern) in Europe. Based on data for all crops, all modelling approaches, all GCM climate models and time slices.

GCM and crop model impacts

The SR also considered the projected change (%) in average yield over time, based on reported time slices (ranging from the 2020s to the 2080s) and for different GCMs (both single and ensemble). The data for all crops and all GCM models are shown in the 'box and whisker' plots in figure 4, disaggregated by EU region. The 'box' defines the inter-quartile range. The line spanning the box represents the median and the 'whiskers' represent the lower (10%) and upper (90%) deciles. Outliers are shown as individual points. The data in figure 4 highlight the significant differences between time slices and regions. Overall, the variation in projected change in average yield is positive across all time slices and regions (apart from southern Europe in the 2080s). There are smaller projected changes in yield for the 2020s compared to the 2050s and 2080s. The inter-decile range spans the zero variation line for all time slices and regions. Generally the variation in projected change in average yield increases with time, and most notably for southern Europe.

Forecasting future crop productivity under a changing climate is subject to several sources of uncertainty, including for example, the timing of impacts (Challinor *et al* 2014). The choice of a particular GCM climate model and whether it is used in isolation or as part of an ensemble can also have a significant impact (Challinor *et al* 2009). Figure 5 shows the projected change in average yield for studies that used either an individual GCM model (e.g. CGCM, ECHAM, HadCM3) or an ensemble approach. Surprisingly, the projected change in average yield was more variable for ensemble-based studies and the median was greater. This is in contrast to findings from a SR of equivalent climate impact on crop yield data for Africa and S Asia (Knox *et al* 2012).

The complexity of modelling approaches used for climate impact assessment can also strongly influence the projected crop yield variation. For example, figure 6 shows the reported yield variation based on either a simple modelling approach, typically based on locally developed statistical models, or a more complex biophysical modelling approach using locally calibrated and validated crop models such as those embedded within DSSAT (Jones *et al* 2003) or standalone crop models such as WOFOST (van Diepen *et al* 1989) or CropSyst (Stockle *et al* 2003). The variation around the mean is much greater for those studies that adopted a complex modelling based approach, with wide variation in both positive and negative yield change. Various authors have previously identified possible reasons (termed 'effect modifiers' in SRs) for

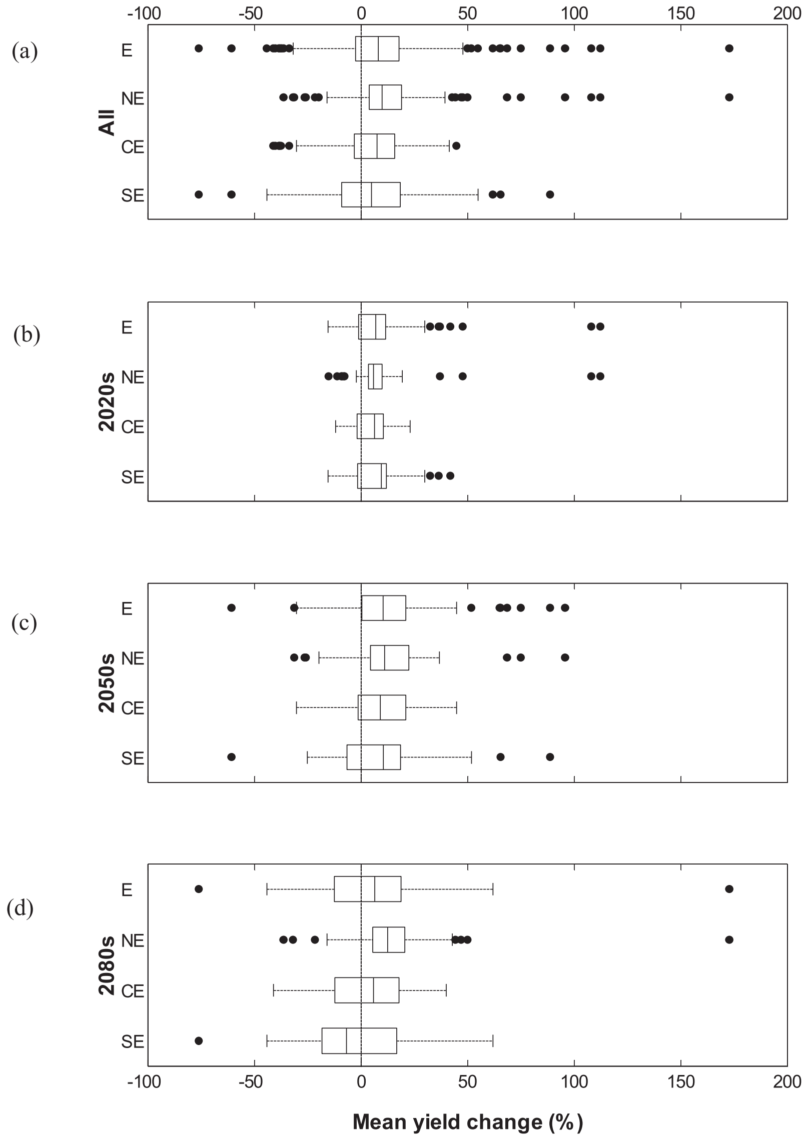

Figure 4. Box and whisker plots showing the variation in projected change in average yield (%) for (a) all observations ($n = 729$) by region in Europe and for selected time slices including the 2020s (b), the 2050s (c) and the 2080s (d).

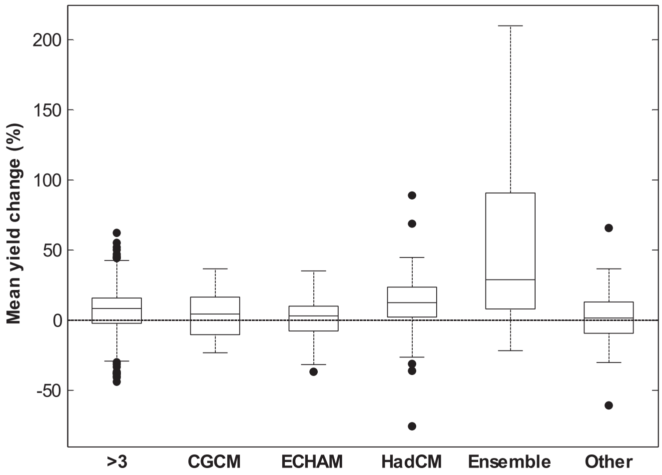

Figure 5. Box and whisker plot showing projected changes in average yield (%) for all crops using either a single, ensemble or group (>3) of GCM climate models.

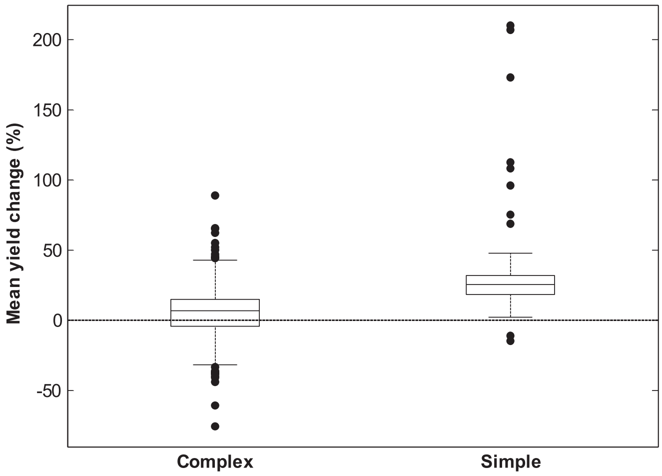

Figure 6. Box and whisker plot showing projected changes in average yield (%) for all crops and time slices, aggregated by climate change modelling approach (complex, simple).

such variation. Firstly, there are more published studies based on the 'complex' modelling approach; in this study, the observations for simple approaches ($n = 70$) was much lower compared to those using 'complex' approaches ($n = 654$). Other factors include differences in the assumptions made in the crop modelling (e.g. soil and crop cultivars, crop management practices, pest and disease risk) and the lack of locally specific model parametrization (Müller *et al* 2011). Finally, different protocols used by researchers could also introduce biases that limit any further cross-study or cross regional synthesis (White *et al* 2011).

Methodological limitations

SRs were originally designed for application in clinical research to synthesise the outcomes from replicated, controlled medical trials where the effects of particular interventions could be identified and quantified statistically. However, in field crops research it is generally not possible to evaluate future climate impacts on crop production through experimentation, so yield impact is usually assessed through a combination of estimation methods involving biophysical or statistical crop models, which themselves introduce an important component of uncertainty into the modelled results due to their simplification of real-world complexity. The quality of primary data available for conducting a SR is also critical. This review was limited to evaluating modelled results from a wide spectrum of climate change impact studies, all of which inevitably contained different combinations of effect modifiers. These included, for example, different emissions scenarios applied to a diverse range of GCMs under various agro-ecological conditions, and varying assumptions regarding crop varieties, agricultural systems, crop husbandry practices, and levels of mechanisation. As highlighted by Reidsma *et al* (2010) such differences in farm characteristics (e.g. production intensity, farm size) are particularly important when considering climate impacts on production and farm adaptation options and responses. In addition, the different spatial scales reported in the literature may explain some of the observed differences together with the approaches used by individual studies for downscaling coarse resolution climate data. The studies included in the SR assessed the impacts of climate change on the crops in the locations where they were currently grown, so they ignored any possible impact of changes in cropping pattern to exploit more favourable growing conditions. Finally, the SR was limited to assessing climate impacts on yield, ignoring any planned or autonomous adaptation or adaptive capacity response; future SR studies could focus on the extent to which adaptation is integrated into crop modelling studies (Reidsma *et al* 2010).

Policy implications for adaptation

This study provides the first SR of climate impacts on crop productivity for a major food production region. The outputs provide valuable new information to inform policies regarding climate change impacts in support of developing adaptation strategies to increase the future resilience of European food crop systems. In contrast to crops such as wheat ($n = 293$) and maize ($n = 149$) where there is extensive and robust evidence, the SR has identified a major knowledge gap regarding the climate impacts on important crops such as barley, rice and rye ($n = 69$, $n = 2$, $n = 4$, respectively). For countries where these crops are important, this will inevitably limit decision makers' and farmers' ability to benefit from research in developing robust strategies to increase their resilience to a changing climate. Surprisingly, the SR also confirmed there is extensive evidence on climate impacts on crop production for northern and central Europe, but much fewer studies for southern Europe.

For the science community, our outputs should help focus future efforts regarding the choice of crops and regions within Europe where research effort is needed and where programmes such as the FACCE JPI (Modelling European Agriculture with Climate Change for Food Security) might wish to direct increased attention. This will assist policy makers and practitioners in making more informed decisions on how and where resources should be allocated to better adapt agricultural production to climate change, and importantly the scale at which interventions should be made. To be effective, adaptation responses at regional level need to be closely aligned and sensitive to the composition and mix of farm types at local level. For example, farmers surveyed by Olesen *et al* (2011) reported a high proportion of negative expectation regarding the impacts of climate change on crop production across Europe, even in the cooler temperate latitudes of northern Europe. This potentially highlights a lack of effective knowledge transfer and dissemination of research to the farming community and practitioners from modelled studies that predominantly demonstrate a positive benefit from climate change on crop production in that region whilst not to excluding the secondary impacts of climate change linked to crop production including potentially increased risks from soil erosion, changes in nutrient cycling and need for crop protection (Olesen *et al* 2011).

Robust and reliable evidence are of course critical in support of formulating policies to address climate impacts on agriculture, food security and trade; implemented effectively it can usefully guide decisions on policy, highlight options for action and identify evidence gaps (Elbehri *et al* 2015). However, from a policy perspective, it is important to recognise that whilst quantifying changes in yield is essential for on-farm adaptation, it constitutes only part of a much broader mix of climate risks to agriculture. Integrated assessments attempt to overcome this by factoring in the links and feedbacks between agricultural production, food demand, markets and land use trends, to identify a range of policy alternatives. Various international collaborative initiatives are striving to achieve this through linking global circulation models with biophysical and agricultural economics modelling to inform economic and trade impacts at the regional and international levels (Rosenzweig *et al* 2013). Given the strong differences in climate yield impact between Europe and other regions, and the fact that climate change can transform trade by altering the comparative advantages between regions (Elbehri *et al* 2015), there will also be a need for more climate-compatible trade policies to resolve the trade versus environment trade-offs to ensure that future trade regulations are more tightly aligned with climate adaptation objectives. Recent research has also highlighted the policy risks associated with conducting single-sector (e.g. agriculture, forestry) climate impact assessments. In Europe Harrison *et al* (2016), showed how single sector studies can strongly misrepresent the spatial pattern, direction and magnitude of most impacts as they omit critical interdependencies between human and environmental systems. Finally, developing policies to achieve a more climate resilient agricultural sector in Europe will require much greater attention to the links between water resources and agricultural production. Since water mediates much of the climate impact on agriculture any projected increases in water scarcity will inevitably present major challenges for climate adaptation, food security and nutrition (Elbehri *et al* 2015). Identifying ‘hotspots’ where irrigated agriculture is concentrated and where future supply-demand imbalances might occur, could provide valuable insights to inform national policies targeting resources for adaptation, or in providing incentives for adaptation research to identify more resilient agricultural technologies/systems in hotspot regions. National climate change policies should also pay greater attention to identifying regions where future investment in agriculture and new food crops should be encouraged, particularly where more favourable growing conditions and/or new markets might emerge. Clearly, there are many opportunities for robust evidence derived from SRs to usefully contribute to ongoing policy dialogue and science debate.

The evidence from this SR confirms that climate change is likely to increase the yield of Europe’s major agricultural cropping systems, with more favourable impacts in northern and central Europe. Despite the inherent limitations in applying an SR approach in this research domain, it highlights a potentially very important message; that climate impacts in Europe are not necessarily all negative, but that they could be beneficial for many crops and areas of production. This could also trigger changes in growing conditions and land suitability for other crops that are currently either marginal or not grown by farmers in certain regions, providing scope for crop diversification. Notwithstanding these potential opportunities, as stated by Wheeler (2015), the multitude of risks that climate change still poses to agricultural output and food systems in Europe and globally should not be ignored by those making medium to long term strategic planning decisions regarding food security.

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referred to in this article should be directed to researchdata@cranfield.ac.uk.

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