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Climate change impacts on crop productivity in Africa and South Asia

Jerry Knox¹, Tim Hess¹, Andre Daccache¹ and Tim Wheeler²

¹ Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

² Walker Institute for Climate System Research, Department of Agriculture, University of Reading, Reading RG6 6AR, UK

E-mail: j.knox@cranfield.ac.uk

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Abstract

Climate change is a serious threat to crop productivity in regions that are already food insecure. We assessed the projected impacts of climate change on the yield of eight major crops in Africa and South Asia using a systematic review and meta-analysis of data in 52 original publications from an initial screen of 1144 studies. Here we show that the projected mean change in yield of all crops is -8% by the 2050s in both regions. Across Africa, mean yield changes of -17% (wheat), -5% (maize), -15% (sorghum) and -10% (millet) and across South Asia of -16% (maize) and -11% (sorghum) were estimated. No mean change in yield was detected for rice. The limited number of studies identified for cassava, sugarcane and yams precluded any opportunity to conduct a meta-analysis for these crops. Variation about the projected mean yield change for all crops was smaller in studies that used an ensemble of >3 climate (GCM) models. Conversely, complex simulation studies that used biophysical crop models showed the greatest variation in mean yield changes. Evidence of crop yield impact in Africa and South Asia is robust for wheat, maize, sorghum and millet, and either inconclusive, absent or contradictory for rice, cassava and sugarcane.

Keywords: climate change, crop, yield, model, Africa, South Asia

 Online supplementary data available from stacks.iop.org/ERL/7/034032/mmedia

1. Introduction

Although global food production has been rising, the world still faces a persistent food security challenge (Pretty *et al* 2003). By 2050 the world will need to increase crop production to feed a projected nine billion people, in the face of changing consumption patterns, the impacts of climate change and growing scarcity of water and land (Beddington 2010). Sub-Saharan Africa (SSA) is often cited as one of the most vulnerable regions (Slingo *et al* 2005) since it maintains the highest proportion of malnourished populations in the world; a significant portion of its national economies are dependent on agriculture (Schlenker and Lobell 2010,

Benhin 2008), and most of its available water resources (85%) are used for agriculture (Downing *et al* 1997). Farming techniques are also relatively primitive, the majority of the continent is already arid and the smallholder systems that dominate the agricultural landscape have very limited capacity to adapt (Müller *et al* 2011). Similar issues exist in South Asia, where more than 75% of the region's rural poor are dependent on rainfed agriculture, livestock and forestry for their livelihoods (World Bank 2009).

Despite international negotiations to reduce greenhouse emissions, a 20–30 year lag in our global climate system means that we are already committed to a world that will be, on average, 0.6°C warmer by the end of the century, with associated changes in rainfall patterns (Solomon *et al* 2007). According to regional climate projections given in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), for Africa warming is very likely to



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be larger than the global annual mean warming throughout the continent and in all seasons. For South Asia, warming is likely to be above the global mean (Christensen *et al* 2007). For annual rainfall it is likely to decrease across much of Mediterranean Africa and in the Northern Sahara region. It is reported that rainfall in southern Africa is likely to decrease in much of the winter rainfall region, and there is likely to be an increase in annual mean rainfall in East Africa. Summer precipitation, the frequency of intense precipitation and tropical cyclones are all likely to increase in South Asia (Christensen *et al* 2007).

The projected spatial and temporal changes in precipitation and temperature will shift current agro-ecological zones (Kurukulasuriya and Mendelsohn 2008) and have major impacts on the viability of both dryland subsistence (Challinor *et al* 2007) and irrigated crop production (Knox *et al* 2010). As climate is a primary determinant of agricultural productivity, any changes will influence crop growth and yield, hydrologic balances, supplies of inputs and other components of managing agricultural systems. Yet the nature of these biophysical effects and the human responses, including adaptation, remain complex and uncertain (Adams *et al* 1998).

Given global concerns regarding the vulnerability of certain staple crops in some regions (Lobell *et al* 2008) and the need to adopt better evidence-based approaches to inform policies, here we present the findings from a systematic review and meta-analysis of the projected impacts of climate change on crop productivity in Africa and South Asia over a range of time horizons. Similar analyses have been conducted by Roudier *et al* (2011) and Müller *et al* (2011) but the geographical extents, methodologies used and reported number of studies included were quite different. For example, Müller *et al* (2011) focused only on African cropping based on 20 studies (14 quantitative, 6 qualitative) and did not consider climate risks by crop or region. The research presented here draws on a much larger dataset of published literature, and provides evidence for eight crops covering both Africa and S. Asia, at a regional level. The study by Roudier *et al* (2011) focused only on West Africa. Finally, neither Roudier *et al* (2011) nor Müller *et al* (2011) explicitly stated that their methodology followed the highly structured approach of a 'systematic review' which compared to conventional reviews avoids the risks of bias associated with including or excluding specific literature which could then have a major influence on the study outcomes.

In our analysis, the productivity impact (i.e. yield per unit area) is expressed here as the yield 'change'—that is the projected yield for the given future scenario as a percentage change against current, or baseline, yield. The analysis was conducted for eight food and commodity crops (rice, wheat, maize, sorghum, millet, cassava, yam and sugarcane) which collectively account for over 80% of total crop production in Africa and South Asia (FAO 2010). The systematic review included biophysical based crop modelling studies and statistical studies using GCM climate projections, but excluded those concerned with the underlying science of crop response to one or more climate factors.

2. Methods

We used a highly robust and rational systematic review (SR) methodology to synthesize the scientific evidence from a range of sources. Our approach followed the systematic review guidelines developed by the Collaboration for Environmental Evidence (CEE) and Centre for Evidence Based Conservation (CEBC 2010). This included the drafting of a protocol to define the methods, followed by systematic literature searches and selection of literature based on a defined set of 'inclusion criteria'. The protocol defined the methods for data extraction, development of the meta-database and data synthesis (see supplementary information (available at stacks.iop.org/ERL/7/034032/mmedia) for a detailed account of the individual stages in the SR). Our study focused on the biophysical aspects of climate change impacts on crop productivity (i.e. yield per unit area) and did not consider 'food production', as this is dependent on many other 'non-biophysical' factors, such as irrigation investment, international trade policy and world markets. It also ignored the impact of any climate related shocks such as floods, droughts and pest attacks on food production.

Following CEE convention, the research question was broken down into components, considering (i) the Population (agricultural 'food' crops, excluding 'non-food' sectors), (ii) Interventions (projected climate changes based on various general circulation models (GCM), and a timescale up to the 2080s; temperature (mean, seasonal variation) and rainfall (mean annual and seasonality) as the main climate variables, including changes in CO₂ concentration), (iii) Comparators (changes relative to a baseline, defined as 1961–90 to match the World Meteorological Organisation (WMO) standard) and (iv) Outcomes (defined as changes in average yield and variation of yield). These are collectively known as the 'PICO terms' in a systematic review. Specific PICO keywords were also defined, relevant scientific (ISI Web of Knowledge, Scopus, ScienceDirect, Ingenta Connect) and other (EBSCO GreenFILE, CSA Natural Sciences, Directory of Open Access Journals, FAO Repository) databases identified and search terms developed and applied to each database (see supplementary information available at stacks.iop.org/ERL/7/034032/mmedia for further detail on each of these aspects). Academic sources were sampled first, to avoid duplication later from less specialized databases. For the internet, website searches using the same search strings were also conducted and a maximum of 50 'hits' reviewed. All references retrieved from the searches were collated in Refworks, a bibliographic software package, prior to an assessment of subject relevance using defined inclusion criteria. Bibliographies were also searched for their relevance. Only literature published in English were considered with searches limited to published data from 1990 onwards.

The literature was initially screened for relevance using inclusion criteria, which included (i) relevant subjects (countries/regions defined for Africa and S. Asia; any scale from field to region; crops as defined above; small-scale and commercial agriculture), (ii) types of intervention (emission scenarios for time slices up to the 2080s; emission scenarios

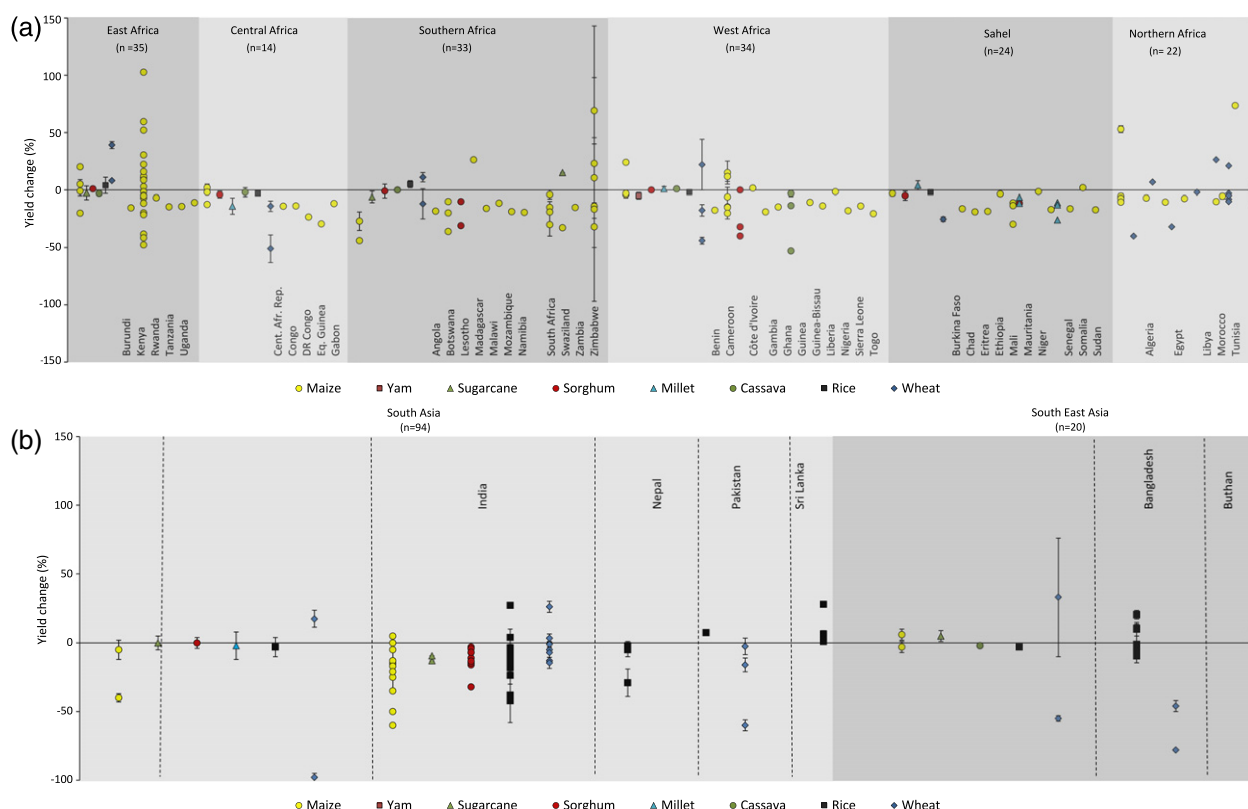


Figure 1. Summary of reported mean yield variations (%) in Africa (a) and S. Asia (b). Data shown are for all observations for each crop type, for all crop modelling approaches, all GCM climate models and all time slices. Where published, the confidence intervals for specific studies are shown.

based on IPCC scenarios; projected changes in mean, total or seasonality), (iii) comparators (future outcomes against present/baselines), (iv) methods (controlled experiments or biophysical modelling), and (v) outcomes (studies relating to changes in crop suitability, performance, variability and/or sustainability). Initial filtering was based on title; then on abstract. The full text was then only reviewed for all articles, reports and papers that passed all inclusion criteria. This was undertaken by two independent researchers to ensure consistency in the acceptance/rejection criteria being applied. We ultimately screened 1144 independent sources of literature—52 were subsequently analysed, representing 257 ‘observations’ of projected yield variation by crop type and region, relative to a historical baseline. These data were collated in a meta-database. A weighted meta-analysis, as would have been used in a conventional systematic review of experimental results, could not be used here due to the inconsistency in the methods of yield estimation and incomplete reporting of the variance. Therefore, mean projected yield variations were compared with a zero response using Student’s *t*-test on the full dataset and then repeated on sub-sets aggregated by time slice, GCM climate model, crop modelling approach, C3 and C4 crop type and geographical region. (A schematic representation of the literature screening process and further detail on the statistical methods is given in supplementary information available at stacks.iop.org/ERL/7/034032/mmedia.)

3. Results and discussion

3.1. Regional climate impacts

The projected climate impacts by crop type, aggregated into sub-regions for Africa (southern, central, east, west, Sahel and northern) and S. Asia (southern and south east) are shown in figure 1. The data relate to the projected mean yield variations for each crop type, for all crop models, all GCM models and all time slices. Where published, the confidence intervals are shown. The primary data are then summarized in table 1. The significance of the mean yield reduction, compared to zero change, was tested using Student’s *t*-test (see supplementary information (available at stacks.iop.org/ERL/7/034032/mmedia) for the countries included and statistical methods employed). Overall, a mean yield reduction of -8% was identified in both Africa and S. Asia, with significant reductions projected for wheat (-12%), maize (-7%), sorghum (-3%) and millet (-9%). However, when the data were broken down by time slice, only projected changes for the 2050s and beyond were significant. It is important to note that projected yield data were not necessarily available for all crops in all regions, so the lack of a significant response may in part be due to the absence, or limited number of studies for certain crops and/or regions. Furthermore, the results include all reported yield projections, for all time slices, for all GCM combinations (whether single or ensemble) and for all crop modelling approaches

Table 1. Summary of reported impacts of climate change on yield (mean and median changes %) for all crops, by sub-region in Africa and S. Asia. (Notes: *n* = Number of reported mean yield changes, which may include several from the same source for different countries or time slices; NS = not significant.)

Crop	<i>n</i>	Mean change (%)	Median change (%)	Crops with significant variation	<i>n</i>	Mean change (%)	Crops with non-significant variation ^a	<i>n</i>
All crops	257	−7.7	−7.0	Wheat	37	−12.1	Rice	43
				Maize	12	−7.2	Cassava	8
				Sorghum	9	−13.0	Sugarcane	7
				Millet	23	−8.8		
Africa	163	−7.7	−10.0	Wheat	20	−17.2	Rice	5
				Maize	10	−5.4	Cassava	7
				Sorghum	6	−14.6	Sugarcane	3
				Millet	13	−9.6		
Southern Africa	33	−11.0	−15.1	Maize	24	−11.4	Wheat	2
							Sorghum	3
							Sugarcane	2
Central Africa	14	−14.9	−12.1	Maize	8	−13.1	Wheat	2
East Africa	35	0.4 (NS)	−2.3	—	—	—	Wheat	2
							Maize	29
West Africa	34	−12.5	−8.4	Maize	19	−7.4	Wheat	3
							Sorghum	5
							Cassava	4
Sahel	24	−11.3	−11.5	Maize	13	−12.6	Sorghum	3
				Millet	6	−10.6		
North Africa	22	0.8 (NS)	−7.3	—	—	—	Wheat	10
							Maize	12
S. Asia	94	−7.7	−5.0	Maize	23	−15.9	Rice	38
				Sorghum	10	−10.8	Wheat	17
							Sugarcane	4
South Asia	74	−8.7	−8.4	Maize	21	−17.6	Rice	26
				Sorghum	10	−10.8	Wheat	13
							Sugarcane	3
South East Asia	20	−3.6 (NS)	−2.5	—	—	—	Rice	12
							Wheat	4
							Maize	2

^a Only crops with more than one observation included.

(whether based on simple or more complex biophysical approaches). This highlights the magnitude of variability that exists when all possible causes of uncertainty are included. Subsequent analyses then disaggregate the meta-database (by time slice, by climate model, and by crop model) to highlight which factors might be contributing most to the projected variations.

For Africa, most of the evidence reviewed projected a yield reduction of up to −40%, across all crop types and sub-regions, although there was a large magnitude of variation in the reported impact (figure 1(a)). Only a small number (*n* = 9) of studies accounting for around 30 observations reported yield increases, mainly for maize grown in East, West and Northern Africa. Most evidence in the scientific literature relates to maize (*n* = 106). Rice, sugarcane and yams account for only 6 of 162 observations for Africa despite the fact that these crops collectively account for 27% of the total cropped

area in Africa (FAO 2010). The estimated mean yield change for West Africa (−12.5%) correlates closely with a median yield loss of 11% reported by other research based on data from 16 published studies (Roudier *et al* 2011). Central Africa has by far the fewest estimates of climate change impacts on crop productivity, highlighting the point that major gaps in climate impact knowledge still exist for particular crops and regions, despite the apparent large evidence base within the scientific literature.

For S. Asia, a similar negative projected impact is shown, but with wider variations among studies (figure 1(b)). The majority of data observations (75%) relate to South Asia (India, Nepal, Pakistan and Sri Lanka) compared to South East Asia (Bangladesh and Bhutan). Most evidence, not surprisingly, relates to rice (*n* = 38) grown in India and some important subsistence crops, such as millet and cassava, for which the climate impact data is incredibly sparse. For

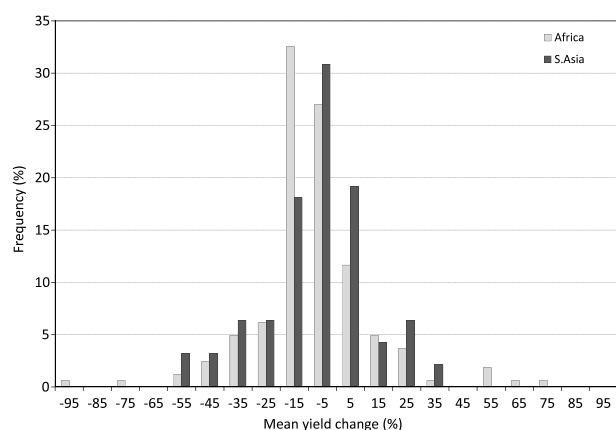


Figure 2. Frequency distribution of the projected mean yield change (%) for all observations ($n = 257$) for Africa and S. Asia. Based on data for all crop types, all crop modelling approaches, all GCM climate models and all time slices.

sugarcane too the lack of evidence is surprising given that it is the third most important crop (after paddy rice and wheat) in terms of value of production in S. Asia (FAO 2010). Robust, scientific evidence on the impacts of climate change on cane yield, as well as for wheat and maize, is thus still very limited.

The projected impacts are also crop and region specific. For example, in Africa, the crops with significant projected yield reductions include wheat (-17%), maize (-5%), sorghum (-15%) and millet (-10%). However, in S. Asia, of the crops reported, only maize (-16%) and sorghum (-11%) are projected to have significant yield reductions (table 1). Despite a relatively large dataset ($n = 43$) the projected mean yield change for rice is not significantly different from zero, with some sources (40%) projecting an increase; others (60%) a decrease; but for several studies, the range straddles the ‘no effect’ line. The variation in projections for rice is also smaller for Africa than for S. Asia, although this largely reflects a smaller number of studies available for meta-analysis. The frequency distributions of the projected mean yield change for all crops (figure 2) shows nearly half of all observations falling within the -15% (-20% to -10%) and -5% (-10% to 0%) bins, although the data for Africa extend across a wider range.

3.2. GCM and crop model impacts

The systematic review also considered projected yield changes over time, based on the reported time slices used for GCM downscaling and crop modelling. Figure 3 shows, for example, the ‘box and whisker’ plot for the projected yield changes (%) for all crops and regions. The ‘box’ defines the upper (25%) and lower (75%) quartiles; the line shown in the middle of the box represents the median and the ‘whiskers’ indicate the 10th (lower) and 90th (upper) deciles. Any outliers in the dataset are shown as individual points. Overall the median projected yield change is negative in all time slices and with smaller decreases projected for the 2020s and 2030s compared to the 2050s and 2080s. However, in all cases the interdecile range (10%–90%) spans the zero

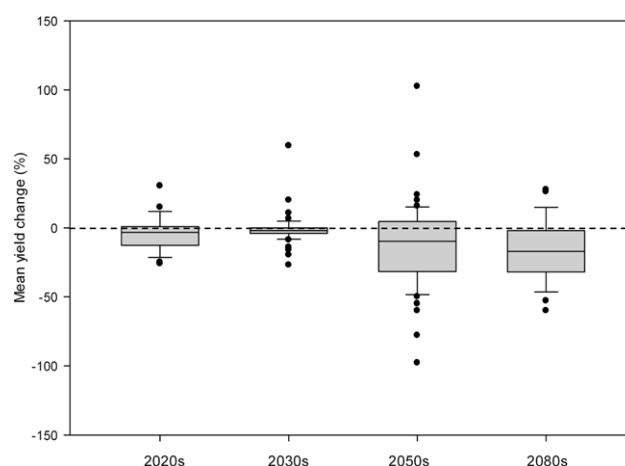


Figure 3. Box and whisker plot of the projected yield changes (%) for all observations ($n = 257$). Based on data for all crop types, all crop modelling approaches, all GCM climate models and regions (Africa and S. Asia) by time slice (2020s–80s).

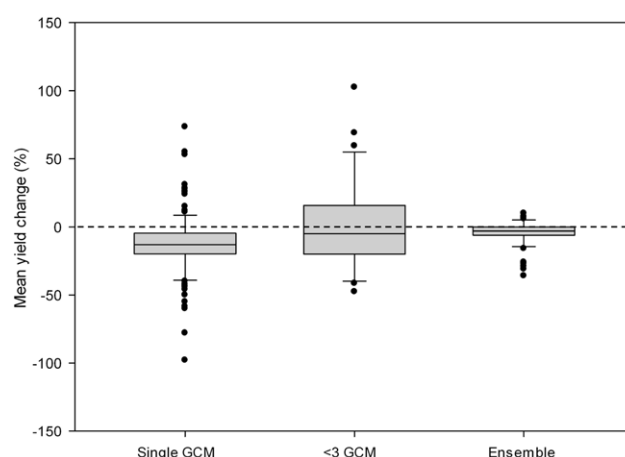


Figure 4. Box and whisker plot of the projected yield changes (%) for all observations ($n = 257$). Based on data for all crop types, all crop modelling approaches, and regions (Africa and S. Asia), by climate model (single GCM, <3 GCM, and ensemble).

variation line and some of the studies reviewed even project a large increase in mean yield. As the climate signal increases, the general trend is that the mean yield productivity decreases with time. However, for most crops and regions, there were either too few studies or no consistent message regarding changes in yield impact over time. Only projections beyond the 2050s and 2080s for maize and sorghum, respectively, were found to be significantly different from zero.

Projections of crop productivity under climate change are subject to uncertainty that can arise from several sources (Challinor *et al* 2009). Increasing the number of climate models that are used for crop simulations reduced the median range and outliers about the mean change in yield (figure 4). Thus, variation in crop projections was reduced by increasing the number of climate models in an ensemble. However, whether such reduction in uncertainty due to ensemble size is simply a confounding of errors or is physically meaningful is not certain (Smith and Stern 2011).

Increasing the complexity of crop simulation also had a strong impact on yield variation. Figure 5 shows the

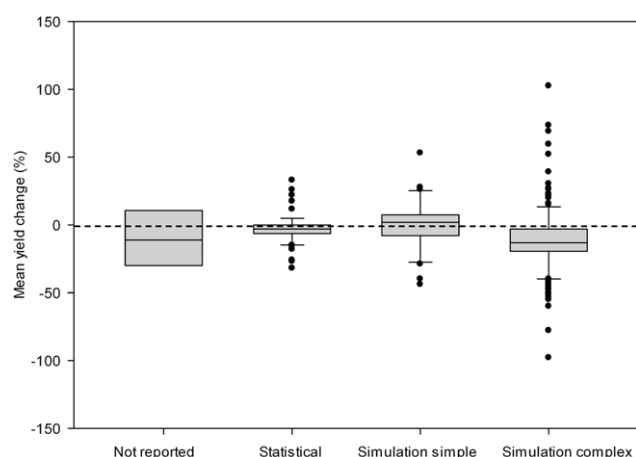


Figure 5. Box and whisker plot of the projected yield changes (%) for all observations ($n = 257$). Based on data for all crop types, all GCM climate models and regions (Africa and S. Asia), by crop model (statistical, simulation-simple, simulation-complex).

projected yield changes for studies based on either statistical models ($n = 62$), simple simulation models such as the FAO agro-ecological zoning approach ($n = 33$), or more complex simulation using biophysical crop models (e.g. CERES, Cropsyst, InfoCrop). Here the variation around the mean increases with model complexity—however, this could be attributed to a number of reasons, including either the larger number of observations using complex simulation modelling approaches ($n = 154$), and/or the combined influence of other ‘effect modifiers’. In this context, the choice of climate modelling approach could account for some of the uncertainty and the large observed range in yield projections (figure 4). This suggests other factors are accounting for the wide spread in modelled yield changes, including the assumptions used in the crop modelling. Others (Lobell and Burke 2010, Lobell *et al* 2011) suggest that such imperfect knowledge of crop modelling inputs is indeed a major constraint since many simulation models were developed for use in temperate systems but lack sufficient data for accurate calibration and validation in developing countries such as Africa where field data is often sparse or non-existent. Others cite the lack of site specific parametrization of the crop management options and cultivars (Müller *et al* 2011), and the risk of model overtuning (Challinor *et al* 2007). Recent research (White *et al* 2011) stressed that the widely varying protocols used by such assessments could also be a potential source of bias that would constrain cross-study syntheses.

The impact of climate change on crop yield will be a balance between yield increases due to elevated CO_2 concentrations (Drake *et al* 1997), any negative effects due to warmer mean temperatures mediated through changes in phenology (Craufurd and Wheeler 2009) and extreme temperature (Wheeler *et al* 2000) and any rainfall limitations to growth, all of which depend on the specific combination of climate projection and the modelled crop response. In the simulations of our meta-analysis, 33.7% and 23.4% of C3 and C4 simulations showed a positive change in yield to climate change, and 66.3% and 76.6% showed a negative change, respectively. A Chi-squared test on that data (pooled

for Africa and Asia) showed no significant difference in the number of positive and negative responses between C3 and C4 crops ($p = 0.07$). This is surprising given expectations of greater benefits to crop yield of elevated CO_2 concentrations for C3 crops compared with those with a C4 photosynthetic pathway and suggest a low sensitivity of crop simulations to elevated CO_2 compared with other weather variables.

3.3. Methodological limitations

The results presented here, like all climate impact assessments need to be interpreted with caution. Systematic reviews are most suited to replicated, controlled (e.g. clinical) trials where the effect of an intervention can be clearly identified. However, the impact of climate change on crop yield is generally estimated from a combination of biophysical crop growth models and climate models, a process which itself is prone to error by the simplification of real-world complexity (Müller *et al* 2011). As a result, some of the variation in yield projection is likely to be due to the differences between the different crop modelling approaches used and the alternative general circulation models (GCM) selected by the researchers. Systematic reviews are also dependent on good primary data. In this study, we were limited to assessing the modelled outputs from a wide range of climate change impact studies, all of which inevitably contain so-called ‘effect modifiers’ or reasons for heterogeneity. These include, for example, different assumed emission scenarios and ensembles, different agro-ecological conditions, and varying assumptions regarding crop varieties, agricultural systems (e.g. rainfed or irrigated) and levels of mechanization and crop husbandry. The spatial scale of enquiry, ranging from detailed local case studies to broad scale regional assessments is also likely to explain some of the reported variation. The modelled yield changes thus inevitably integrate both the projected impacts of climate change and the varying combined effects of many other factors implicit in each of the reported studies. However, notwithstanding these limitations, this study has allowed the results from all available modelling studies to be synthesized in a systematic and unbiased manner, and for general but very important conclusions to be drawn.

3.4. Adaptation and policy implications

Climate change will clearly threaten farming livelihoods of the rural poor in Africa and S. Asia, particularly where soils and climate are already marginal for production and where limited access to agricultural knowledge and technology will hamper their ability to adapt (CCAFS 2009, Lobell *et al* 2008). Some autonomous adaptations, such as shifting planting dates, modifying crop rotations or the uptake of pre-existing crop varieties will help offset some negative impacts of climate change. However, it is reported that the greatest benefits in food insecure regions are likely to arise from more expensive adaptation measures including the development of new crop varieties and uptake of new technologies including, for example, the expansion of irrigation infrastructure (Lobell *et al* 2008). These will

require substantial investments by farmers, governments and development agencies. It is thus vital that any policy decisions to support their implementation, particularly aid investments, are informed by a synthesis of the best available evidence, and not distorted by single studies.

Prioritization of farm level adaptations to climate change will also need to account for the different crops grown within a target region, local farmer attitudes to risk and the time horizons over which investments are made (Lobell *et al* 2008). An important distinction here is between food or subsistence crops grown for local consumption (e.g. cassava, millet) and commodity crops such as sugarcane grown for export. Most of the food crops in this study are grown under rainfed conditions and will be highly susceptible to future changes in soil moisture availability. In contrast, commodity crops are more typically dependent on irrigation to maintain yields, which should help buffer the impacts of changes in rainfall and temperature. However, research shows that even irrigated commodity cropping in Africa will be at risk (Knox *et al* 2010). In many African countries, commodity cropping is a major employer in rural communities, so climate change could affect local populations involved in both subsistence and commercial crop production, albeit in differing ways.

Our findings provide policy makers and practitioners with a robust assessment of the likely impacts on crop yield, and the areas and crops where attention should be focused. Research (Müller *et al* 2011) shows that there is still no comprehensive continent-wide assessment for all major cropping systems in Africa. This study helps to address that research gap by providing the first systematic review of climate impacts on crop productivity in two major food insecure regions, by highlighting important differences in impact between individual crops, continental regions and geographical sub-regions. The analysis has also helped to identify where major gaps in knowledge still exist on the impacts of climate change on yield. For example, figure 2(a) in the supplementary information (available at stacks.iop.org/ERL/7/034032/mmedia) shows the spatial distribution of maize production in Africa derived from crop statistics (FAOSTAT 2012) in relation to the reported number of yield observations for maize. It highlights where there is a growing evidence base, for example, in Kenya, Zimbabwe and Cameroon, and conversely the numerous countries where there is still very limited climate impact evidence despite the importance of maize to agricultural production in those areas (e.g. Nigeria, Tanzania, Malawi). Whether maize yield changes are generally more positive where there are more studies, requires further study (figure 2(b)). Despite the yield change uncertainty and lack of robust data for large parts of Africa and S. Asia, this systematic review provides useful evidence for informing national governments, regional decision makers, and international organizations and in guiding international policy makers and research agendas. Whilst research effort moves towards identifying appropriate adaptation options and responses, for Africa (at least in the short to medium term), it is important that the evidence base on climate change impact on crop productivity continues in earnest.

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