Invited Review: IPCC, Agriculture and Food – A Case of Shifting Cultivation and History

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Complete List of Authors:	Porter, John; University of Copenhagen, Department of Plant and Environmental Sciences; University of Greenwich, Natural Resource Institute Challinor, Andrew; University of Leeds , Institute for Climate and Atmospheric Science, School of Earth and Environment ; Henriksen, Christian Howden, Mark Martre, Pierre Smith, Pete; University of Aberdeen, Institute of Biological and Environmental Science
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Running Title: IPCC, Agriculture and Food

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John R Porter[1,2], Andrew J. Challinor[3], Christian Bugge Henriksen[2], S Mark Howden[4], Pierre Martre[5], Pete Smith[6]

[1]CIHEAM-IAMM – SupAgro - MUSE Univ Montpellier, 34000 Montpellier, France.

[2]Plant and Environmental Sciences, University of Copenhagen, Højbakkegård Alle 26, 2360 Taastrup, Denmark.

[3]Institute for Climate and Atmospheric Science (ICAS), School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.

[4]Climate Change Institute, Australian National University, Canberra, 2600 ACT, Australia.

[5]LEPSE, Université Montpellier, INRA, Montpellier SupAgro, 34000 Montpellier, France.

[6]Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK.

Contact Information John R Porter; +45 29176961 or +336 3535 1498. Email: jrp@plen.ku.dk

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Abstract

Since 1990 the Intergovernmental Panel on Climate Change (IPCC) has produced five Assessment Reports (ARs), in which agriculture as the production of food for humans via crops and livestock have featured in one form or another. A constructed data base of the *ca.* 2,100 cited experiments and simulations in the five ARs were analysed with respect to impacts on yields via crop type, region and whether or not adaptation was included. Quantitative data on impacts and adaptation in livestock farming have been extremely scarce in the ARs. The main conclusions from impact and adaptation are that crop yields will decline but that responses have large statistical variation. Mitigation assessments in the ARs have used both bottom-up and top-down methods but need better to link emissions and their mitigation with food production and security. Relevant policy options have become broader in later ARs and included more of the social and non-production aspects of food security. Our overall conclusion is that agriculture and food security, which are two of the most central, critical and imminent issues in climate change, have been dealt with in an unfocussed and inconsistent manner between the IPCC five ARs. This is partly a result of agriculture spanning two IPCC working groups but also the very strong focus on projections from computer crop simulation modelling. For the future, we suggest a need to examine interactions between themes such as crop resource use efficiencies and to include all production and non-production aspects of food security in future roles for integrated assessment models. (253 words).

1 | Introduction

Agriculture and the local, regional and global food system encompass what most people on Earth do for a living. If one includes the downstream food system from the production to the consumption of food by humans and other animals – the engagement of humans in food security and food production systems dwarfs any other human activity; including computing, pharmaceuticals, the media, energy industry, banking and academia - combined. Agriculture and food production, distribution, marketing and consumption contribute about 30% of global gross domestic product (Braun *et al*. 2017), and have easily higher returns on investment than any economic corporation, sector or activity - but receive only about 5% of global research investment (Pardey *et al*., 2016). Agriculture and food systems however, are highly affected by climate changes and also drive climate change through greenhouse gas emissions and land use change.

The scientific bedrock of the agreement at the 21st Conference Of the Parties (COP21) of the United Nations Framework Convention on Climate Change in Paris in December 2015 were the 5th Assessment Reports (AR5) of the Intergovernmental Panel on Climate Change (IPCC) from 2013 and 2014 (IPCC Assessment Reports are available at https://www.ipcc.ch/reports/). The statement from COP21 reads '*Recognizing the fundamental priority of safeguarding food security …… and the vulnerabilities of food production systems to the adverse impacts of climate change*' acknowledging the central role of food security regionally and globally. Important inter-disciplinary departures in the food security chapter of the IPCC (Porter *et al*., 2014) were recognition of factors other than food production in food security: such factors include food distribution and social and economic access to food, which all stand to be affected by climate change and which have possibilities for adaptation. Food security and agriculture have not always had such a clear or prominent position in IPCC ARs - with food security only specified in AR5 and with agriculture often rolled in with forestry and forest products (AR1 and AR4) or general ecosystem services (AR3). AR2 did examine impacts and adaptation of agriculture. We regard the evolution of a food system perspective in IPCC AR5 as a very positive development that we hope will be amplified in AR6 and future IPCC Special Reports.

This review aims to develop further, and in more detail, the recent paper by Porter *et al*. (2017) on the link between the five IPCC Assessment Reports (AR1 to AR5) and agriculture. Space constraints in that article prevented presentation of topics such as regional differences in assessments of impacts, adaptation and mitigation linked to agriculture; the balance between assessment of climate change and crops versus livestock; the methods used and how and why assessments might develop in the future. Post AR5 (Porter *et al.*, 2014), the Royal Society of London (Royal Society, 2017) published an update on climate change effects on food production. Their conclusion was that post-AR5 studies have confirmed conclusions in AR5, but new studies 'point strongly to the importance of accounting for how land use and cropping intensity might change'. Our review addresses the above gaps and addresses potentially policy-relevant information that has become available since the AR5.

2 | Impacts

To get an overview of the assessment of climate change impacts on crop yield across the five IPCC Assessment Reports, across the different global regions and for the major global crops, we complied all data (*ca*. 2100 entries) on projected crop yield with and without adaptation from AR1-AR5. We constructed a database with information about the AR volume, crop type, livestock, global region and projected mean change and variation in yields with and without adaptation. Subsequently, the average mean change in yield with and without adaptation was calculated for each IPCC Assessment Report, each global region and each major global crop (Tables 1-3). A striking omission across the five ARs is the almost complete lack of quantitative data of the effects of climate change on livestock; no quantitative data were presented from AR1 to AR3 and only 18 cases were reported in AR4 and AR5 combined (Rivera-Ferre *et al*. 2016).

Table 1. Mean percent change in grain yield of all crops reported in AR1-AR5 with and without adaptation.

IPCC AR	With adaptation: Number of cases	With adaptation: Mean change (%)	With adaptation: Standard deviation (%)	Without adaptation: Number of cases	Without adaptation: Mean change (%)	Without adaptation: Standard deviation (%)
AR1	6	9.0	11.5	28	3.4	33.0
AR2	46	-0.2	23.1	53	-13.8	25.8
AR3	57	-8.2	17.4	36	-5.2	23.4
AR4	239	3.6	19.0	320	-4.0	17.7
AR5	519	-3.9	17.2	812	-9.9	19.4

All IPCC Assessment Reports, except AR1 have projected a crop yield reduction without adaptation (Table 1). The largest projected yield reduction was in AR2 with -13.8% followed by -9.9% in AR5. When climate adaptations were included in the analysis, most assessment reports also projected a yield reduction except for AR1 with a 9.0% yield increase and AR4 with a 3.6% yield increase. However, the standard deviations in the projections are large, ranging from 11.5% to 33.0%.

Table 2. (over). Mean percent change in grain yield for different global regions summarized for AR1-AR5 with and without adaptation. When constructing the database, the results from AR1-AR5 were allocated to the IPCC AR5 global regions by following the following rules: data from Russia and former Soviet Union were allocated to the global region North Asia; data from Middle East and North Africa were allocated to the global region West Asia; data from Latin America and the Carribean were allocated to Central and South America; data from south-east Mediterranean (Jordan, Egypt and Libya) were allocated to the global region Africa; data from Pacific Asia and Pacific OECD were allocated to the global region Australasia.

	With adaptation			**Without adaptation**		
Region	**Number of cases**	**Mean change (%)**	**Standard deviation (%)**	**Number of cases**	**Mean change (%)**	**Standard deviation (%)**
Africa	153	-4.2	19.8	274	-9.5	17.7
Australasia	38	6.9	17.7	38	-7.1	21.7
North America	109	1.2	17.3	167	-7.8	25.8
Central and South America	74	-12.6	17.7	91	-12.1	15.8
Europe	68	3.3	22.0	164	-4.3	21.3
North Asia	10	8.9	11.3	6	-14.0	17.7
East Asia	126	-1.5	14.6	175	-4.9	16.3
Central Asia	11	-3.9	18.4	9	-19.2	18.3
West Asia	8	-8.4	6.9	18	-5.0	11.7
South Asia	138	0.1	16.2	199	-11.7	18.9
South-east Asia	31	10.4	20.7	41	-0.6	14.0
Asia (unspecified)	18	-14.0	17.8	6	-2.3	11.2
Global	**74**	**-6.4**	**17.5**	**37**	**-17.9**	**20.1**

The standard deviation is also large for the mean change in yield for different global regions (Table 2). Without adaptation Central Asia had yield change of -19.2%, followed by North Asia with -14.0%, Central and South America with -12.1% and South Asia with -11.7% are the regions with the largest projected yield decreases. With adaptation, South-east Asia, North Asia and Australasia have the largest yield increase with +10.4%, +8.9% and +6.9%, respectively.

Table 3. Mean change in yield for different crops summarized for AR1-AR5 with and without adaptation.

	With adaptation			Without adaptation		
Crop	**Number of cases**	**Mean change (%)**[a]	**Standard deviation (%)** [a]	**Number of cases**	**Mean change (%)**	**Standard deviation (%)**
Barley	1	-35.0	n/a	7	0.7	14.4
Beans	1	45.0	n/a	12	-38.7	37.1
Cassava	0	n/a	n/a	21	-2.2	3.9
Grass	4	11.8	24.	6	-8.5	45.7
Groundnut	3	34.0	17.	11	-6.6	12.5
Maize	303	-5.6	16.	281	-10.8	18.2
Millet	2	-27.0	13.	111	-9.3	20.4
Potato	0	n/a	n/a	19	-2.0	17.4
Rice	140	3.4	15.	231	-5.3	14.7
Sorghum	2	-23.5	37.	21	-9.1	7.8
Soybean	73	-12.8	17.	83	-16.9	27.0
Sugarcane	0	n/a	n/a	18	-2.5	9.8
Sunflower	0	n/a	n/a	10	-3.1	6.1
Sweet potato	0	n/a	n/a	5	-2.2	7.2
Wheat	225	1.9	21.	343	-7.0	20.6

For major global crops (Table 3), it is evident that the crops most severely affected by climate change without adaptation are beans, soybean and maize with yield reductions of -38.9%, -16.7% and -10.8%, respectively. For protein crops, this is particularly alarming given their potential to replace meat-based protein with both health and greenhouse gas emissions benefits

(Tilman and Clark 2014). Also, besides maize, some of the other major staple crops for the Southern Hemisphere are projected to have significant yield reductions without adaptation, e.g. -9.3% for millet and -9.1% for sorghum. Even with adaptation, large yield reductions are projected for maize, millet, sorghum and soybean. Considering that these three crops cover 60% of the area cultivated with cereal crops in Africa and provide 67% of the cereal yield on the continent (Macauley, 2015), a yield reduction of this magnitude would have severe consequences. Overall, adaptation is not projected to have a very large effect on reducing or even reversing yield reductions for the major global crops. Large yield increases can be seen for beans, groundnut and grass, but these results are only based on few observations. Based on this analysis, rice and wheat, with yield increases of +3.4% and +1.9%, seems to be the only major global crops to benefit from adaptation efforts.

3 | Adaptation

From the first IPCC Assessment onwards, a systems approach has been applied to the analysis of climate impacts and adaptation relating to agriculture, food production and, more recently, food systems. However, both the supporting literature and the emphasis and framing of this have changed significantly over the five IPCC ARs, with a relative increase in the number of studies including adaptations to impacts. In AR1, there was relatively little quantitative literature on climate change impacts and so a conceptual systems approach was used to identify the likely impacts and their interlinkages. These included suggestions that changing crop yields could lead to potential changes in geographical distribution of cropping. The focus was on average agricultural production, paleo-analogues and basic physiological responses such as laboratory responses of plants to CO_2 to support scenarios of future impacts. The main focus was on cereal crops rather than livestock or other food-producing systems such as horticulture. Studies were almost exclusively drawn from the temperate zones and from developed nations. Subsequent IPCC assessments of climate impacts on production of the major crops (wheat, rice, maize and soybean) have significantly increased in complexity, drawing from the expanding literature base. The increase in the number and coverage of studies has successively allowed tabulation of crop responses (AR3), and then meta-analyses initially developing simple relationships (AR4) and subsequently statistical relationships between variables (AR5; Challinor *et al*. 2014). In particular the crop modelling studies have evolved from simple, often site-based scenarios driven by fixed temperature and rainfall changes (e.g. +3ºC and -20% rainfall) towards integration of downscaled GCM data in grid-based or multi-site, regional assessments. Nevertheless, the focus of the IPCC remained on mean yield change and it was only in AR3 was there inclusion of a focus on changes in yield variability and, in AR5, the nutritional quality of crops. Whilst there are regional and global crop production studies there are have been few impact studies which have used a value chain or food systems perspective. Developing country studies remain relatively under-represented in terms of population (Table 2), even though developing countries were identified as early as AR2 that they were likely to be the most negatively affected. Similarly, even though AR2 concluded that elevated atmospheric CO_2 concentrations would have beneficial impacts on crop production, there remained active debate in AR5 about the degree to which this may affect crop yields and quality.

As noted above, there has been relatively little quantitative treatment of livestock (Rivera-Ferre *et al*. 2016), other field-crops, horticulture and viticulture across IPCC reports with coverage being largely restricted to either generic, system-level responses or site-specific cases, largely because of the relative lack of studies using somewhat-comparable modelling or other analysis methods in contrast to the mechanistic and other crop models, which have enabled meta-analysis, cross-model comparison and assessment of uncertainties (Rosenzweig *et al*. 2014). The treatment of weeds, pests and disease impacts are also inconsistently dealt with across the reports.

The aggregation of climate change impacts on food production systems to broad-scale economic and food price impact was also initiated in the AR2 with results reported from one economic model. Successive IPCC Assessment Reports have synthesised the rapidly developing literature to not only address global and regional impacts of climate trade on prices, production and trade but also the uncertainties in model results and the reasons behind these (Nelson *et al*. 2014).

Adaptation to the sorts of climate change impacts noted above is a fundamental part of risk management. Agriculture and food producers as well as value chain managers, consumers and policy makers have shown considerable ability to adapt to climate changes both currently and going back into history; for instance, the establishment of grapevines in England in Roman times or the settlement of Greenland in medieval times. The expectation that adaptation of food systems is likely to be both feasible and attractive has resulted in coverage from AR1 onwards. However, the framing, scope, likely effectiveness and analytical methods used in IPCC reports has changed significantly since then (Table 4). There remain many gaps in terms of adaptation of food systems including, but not limited to, the need to include assessment of more systemic and transformative adaptations, adaptation of value chains and of regional food systems. Other important issues for the future include how to address the multitudinous barriers to adaptation, developing the pathways to not only build adaptive capacity but to also move this into adaptation actions, developing policies and programs to establish effective monitoring, evaluation and attribution of adaptation and assessments and to more effectively address net greenhouse gas emission reduction within adaptation strategies. This latter point is starting to be addressed in the IPCC AR6 cycle, being covered by two Special Reports (www.ipcc.ch/reports) as well as within the main Assessment Reports.

Table 4. The framing, scope and analysis methods used to address climate adaptation in agricultural and food systems in successive IPCC Assessment Reports (ARs).

IPCC Assessment	**Framing, scope and analysis methods used**
AR1	*Framing*: Three adaptation domains - physiological adaptation, farm level management ‘adjustment’ and responses arising from policy at regional, national and international levels. These were expressed in terms of enabling farming systems to reach a new equilibrium in response to altered climates. *Scope*: Farm-level, production focus not food systems. *Analysis*: Generally, adaptations were described qualitatively using historical analogues or first principles approaches rather than quantified responses.
AR2	*Framing*: Spontaneous or planned adaptation, in response to or anticipation of climate change. *Scoping*: Farm-level production focus not food systems with brief reference to global economic analyses of producer surplus, which included with and without adaptation. *Analysis*: Few quantitative adaptation studies although most adaptation options were raised based on a systems view. However, these were mostly incremental such as agronomic adjustments although there were some systemic adaptations (*sensu* Rickards and Howden, 2012) such as the introduction of new species. There was a recognition that successful adaptation depends upon technological advances, institutional arrangements, availability of financing and information exchange as well as adaptive capacity and alignment of the options with farmer needs so as to enhance adoption paths. Additionally, there was recognition of the possibility of policy maladaptation.

AR3	*Framing*: No specific framing, focused on farm-level, agronomic changes. *Scope*: Farm-level production focus not food systems, with examples of integrated regional economic analyses of impacts and adaptation. *Analysis*: As well as qualitative discussion of options such as crop breeding to adjust to elevated CO_2 and temperatures, there were more quantitative analyses of cropping system adaptations allowing both tabular and figure summaries of the modelled effectiveness of adaptation. However, there was a critique that methodologically, there had been little progress since the previous IPCC Assessment with the adaptation strategies being modelled limited to a small subset of the possible options and unrealistic assumptions regarding the degree and effectiveness of farmer adoption. There was recognition of adaptation costs including transition costs, dislocation costs and capital and operational costs. There was however, limited coverage of livestock adaptation with discussion of a range of management adaptations to reduce the effects of heat waves but few quantified or modelled analyses to draw from.
AR4	*Framing*: Autonomous and planned adaptation modes. *Scope*: Recognition of the importance of a food systems approach but the focus remained on agricultural production. *Analysis*: Discussion of a broader range of possible adaptation options for both cropping and livestock using a more structured approach particularly drawing off the burgeoning literature on cropping system impacts and adaptations. This allowed more geographically explicit analyses as well as a meta-analysis of impacts and adaptation as a function of temperature increase. However, most adaptation options addressed were still incremental in nature, reflecting in part limitations of the modelling approaches being used. There was a critique of the

	failure to provide generalised knowledge of adaptive capacity, of adoption pathways and barriers to these and of a more comprehensive range of adaptation strategies especially beyond simple, single agronomic changes. There was still limited evaluation of the costs of adaptation or of consequences of adaptation in relation to the environment and the natural resource base.
AR5	*Framing*: incremental to transformational adaptation. *Scope*: Food systems approach although much of the literature able to be synthesised was on food production only. *Analysis*: Discussion of a broad range of possible adaptation options and their adoption paths for both cropping and livestock using a consistent framing. The further increase in the literature on cropping system impacts and adaptations allowed 1) an improved meta-analyses of impacts and adaptation as a function of temperature providing finer-grained information across the major crops, by broad region and disaggregating results to allow assessment of the effectiveness of different agronomic adaptation options; and 2) a meta-analysis of the possible increase in crop yield variability over time. Livestock adaptations were not able to be dealt with as comprehensively as cropping systems due to limitations in the literature. There was increased recognition of the importance of institutional limits and adoption barriers but some other issues identified as shortcomings in prior IPCC Assessments remain largely unaddressed (e.g. adaptation costs, lack of methodological innovation and diversity in adaptation analysis).

4 Mitigation

For mitigation potential in the agriculture sector, methods have changed markedly over the course of the IPCC Assessment Reports. Bottom-up methods, assessing mitigation potential practice-by-practice using data on land areas and livestock numbers available, were used in AR1 and AR2. AR3 largely replaced this approach with a top-down assessment from integrated assessment models (IAMs). For both AR4 and AR5, both bottom-up and top-down estimates were included in conjunction. IAMs have the advantage that they can consider mitigation options across sectors and select least-cost options and pathways for mitigation, which bottom-up approaches cannot. Their disadvantage, however, is the limited number of agricultural options that they include, which are mostly confined to non-CO_2 greenhouse gases. Bottom-up methods, on the other hand, capture the rich detail of the agricultural practices available (Bennetzen *et al.*, 2016) but are unable to consider mitigation across sectors, so estimates of economic potential are more uncertain. The combination of top-down and bottom-up approaches will likely prove useful again in AR6.

Chapters dealing with climate change mitigation in the IPCC Assessment Reports have been weak in linking emissions with the primary purpose of agriculture, i.e. producing food. For example, demand-side measures to limit greenhouse gas emissions through changes in human diet or through waste reduction were not considered in detail until AR5. Systematic changes in the food system have been under-represented compared to technical interventions, such as changes in fertilisation, livestock feed-additives and changes in tillage practice, on farm. This is perhaps driven by the sectoral approach taken in most assessments. For example, greenhouse gas emission reductions through fossil fuel offsets by production of bioenergy are not accounted for in the agriculture sector, so are not reported in the agriculture or land chapters. Reduced energy consumption in agriculture is not reported in the agricultural and land sector, nor any emission reductions associated with improved packaging, transport, distribution and storage.

Taking an approach based on the sectors from which emissions are reported is logical, but does not encourage food systems approaches to addressing emission reduction goals. Future assessments will need to take a more holistic view of the food system, and go beyond the accounting / reporting sectors considered to date.

Another persistent issue across IPCC Assessment Reports arises from the structure in which assessments are conducted, with Working Group 1 focussing on the physical science basis of climate change, Working Group 2 focussing on impacts of climate change and adaptation, and Working Group 3 focussing on mitigation. The chapters dealing with agriculture and land in each Assessment Report are written by different authors and appear in different volumes, corresponding to each Working Group. While efforts are made to encourage cross-working group / cross-volume collaboration and consistency, results have been uneven, with a number of disconnects in emphasis across the volumes.

The IPCC Special Report on Climate Change and Land, under production as part of the AR6 cycle and due in 2019, offers an opportunity to address some of the issues raised above. Firstly, it is a joint action across the three Working Groups, thereby including experts from more disciplines than usually found within Working Groups. Secondly, it considers a wide range of land and climate change related issues, including mitigation, adaptation, desertification, land degradation, sustainable land management and food security. With an emphasis on integrated response options to address all of these challenges, considering synergies and trade-offs, it necessarily takes a broader view of land, agriculture, food systems and the interventions available to address the considerable challenges facing humanity now and in the future. While examining all of these factors together is extremely challenging, due to the complexity of the sectors involved, the importance of food and agriculture and climate change for the future of humanity means it is a challenge that must be met. Future IPCC Assessment Reports could learn from the experience of producing this Special Report – to take a broader view of the issues facing land and agriculture, and to facilitate cross Working Group integration.

5 | Policy

The policy elements of climate adaptation and mitigation in relation to agriculture and food systems have been addressed unevenly and incompletely over the various Assessment Reports. AR1 acknowledged the importance of a range of policies (listing food price, land-use, forest resources, extension and water transfers) but required more information in relation to potential responses. AR2 expanded the list to include research, land-use planning, water pricing and allocation, disaster vulnerability assessment, transport and trade policy and policies countries use to encourage or control production, limit food prices and manage resource inputs to agriculture. There was a brief critical analysis of how policies may discourage adaptation strategies and acknowledgement of the political, economic and cultural factors at play but overall very little concrete guidance in relation to policy design and development. In contrast, the AR3 and AR4 provided few linkages to policy and it was not until AR5 that more policy-relevant suggestions were developed. These included *inter alia* capacity building across the food system via support of monitoring and communication, systems analysis, extension capacity and industry and regional networks that develop social capital and share information, supporting community partnerships in developing food and forage banks, enhancing investment in irrigation infrastructure and efficient water use technologies, revising land tenure arrangements (including attention to well-defined property rights), establishment of accessible, efficiently functioning markets for inputs and outputs (seed, fertiliser, labour, water, products, greenhouse gases emissions, etc.) and for financial services, including insurance. There was also introduction of ideas relating to modes of operation such as policy ‘mainstreaming’ and policy analysis methodologies such as the need for multi-level assessment. Importantly, these policy inclusions in AR5 were consistent with moving away from the previous ‘agricultural production' focus to a more 'food systems' focus but nevertheless did not substantially progress the integrated treatment of climate adaptation and mitigation.

6 | Future improvements in examining impacts and adaptation

6.1. | Assessing crop growth models skills to predict interactions between resource use efficiencies

The main types of models used in IPCC impact assessments on crop production fall into the category of crop simulation models, that attempt to predict yields based on bio-climatic inputs and are mostly site-based; statistical relationships have also been used (Porter *et al*., 2014). Such models are only just being used to examine CO_2 and other effects on yield and its protein concentration (Asseng *et al*., 2019) even though this topic has been a persistent theme in the ARs. Thus as suggestions, we wish to highlight the need to analyse the interactions between resource use efficiencies to change the consistent of crop models and better understand cropping systems response to climate change and a topic, focused on modelling. We think this is an important topic for future assessment of climate impacts, adaptation and mitigation within the land-sector and agriculture and their position and role in climate change.

Bennetzen *et al*. (2016) showed via a historical deconstruction analysis, using a modified Kaya identity analysis (Kaya and Yokoburi, 1997), that greenhouse gas emissions from agriculture have decoupled from food production since 1970, and give grounds for optimism that agriculture can make a substantial contribution to reducing global emissions as well as helping to store carbon in land. A reduction of emissions per unit product means that the utilization efficiency of the principle inputs into food production, namely water and fertilizer, has increased. At the same time crop simulation models have been used extensively to project the impacts of changes in CO_2, temperature, rainfall and other factors for global and regional productivity of crops (e.g. Ruane *et al*., 2017). Resource utilisation efficiencies do not operate in isolation; that is to say that there are interactions between, for example, a crop’s utilisation efficiency of water, nitrogen and photosynthetically active short-wave radiation. How far these interactions of resource utilisation efficiencies are incorporated into crop models is unclear and needs testing, together with a critical need to design and make experiments to test the models. Models should not get the ‘right’ answers for the ‘wrong’ reasons such as via cancellation of errors (Challinor *et al*., 2014; Martre *et al*., 2015).

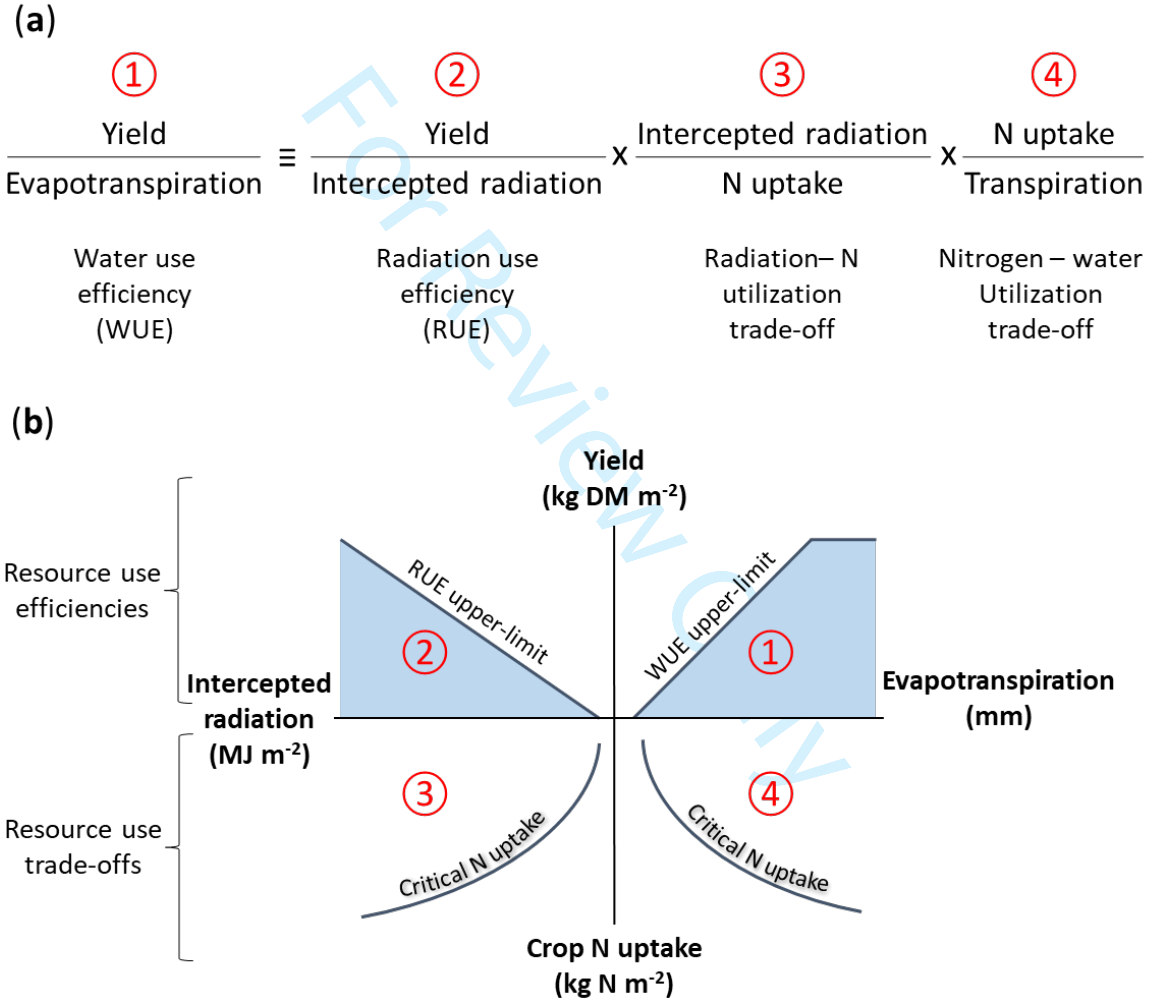

Figure 1. Decomposition of water use efficiency. In (**a**) identity showing the relationship between water (WUE) and radiation (RUE) use efficiencies and water, nitrogen and light utilization trade-offs. In (**b**) four quadrants visual representation of the identity shown in (a). In quadrants 1 and 2, the thick lines are the upper limits of RUE and WUE, respectively. In quadrant 1, the plateau is the potential grain yield defined as the grain yield that can be attained by current cultivars grown in an environment to which it is adapted with water, nutrients and other abiotic and biotic factors controlled effectively (Evans and Fisher, 1999). In quadrants 3

and 4, the thick lines are critical N uptake, defined as the minimum N uptake for achieving maximum above ground biomass at the upper limits WUE and RUE, respectively.

To this end, we propose a methodology based on mathematical identities (Porter *et al*., 2013) that decomposes water and nitrogen utilisation efficiencies and portrays their interactions or trade-offs with water utilisation efficiency. The ideas stem originally from the work of CT de Wit and his colleagues at Wageningen, NL and have been developed by others (Teixera *et al*., 2014; Sadras, 2016) but has seemingly not as yet penetrated crop modelling as an issue for climate change impacts (Ruane *et al*., 2017) . The identity for water utilisation efficiency (WUE) and its graphical portrayal (Figure 1) show a possible relationship between WUE and radiation utilisation efficiency (RUE). Questions for that need responses from crop models including ‘what are the modelled upper limits for RUE and WUE in ambient and changed climate pathways and how do they compare with observations?’ and ‘In comparison with a control treatment, how do the utilisation efficiencies change and interact?’ Crop models should be able to populate such analyses and we give an example (Figure 2) using the *SiriusQuality* wheat model (Martre *et al*., 2006; Martre and Dambreville, 2018; http://www1.clermont.inra.fr/siriusquality/). The simulations are of a four-year CO_2 enrichment experiment on spring wheat at Maricopa, USA (Kimball *et al*., 2017) in which the crops were grown in ambient and elevated CO_2 for combinations of either high or low levels of nitrogen and of either full or reduced irrigation (see Figure 2 caption for details).

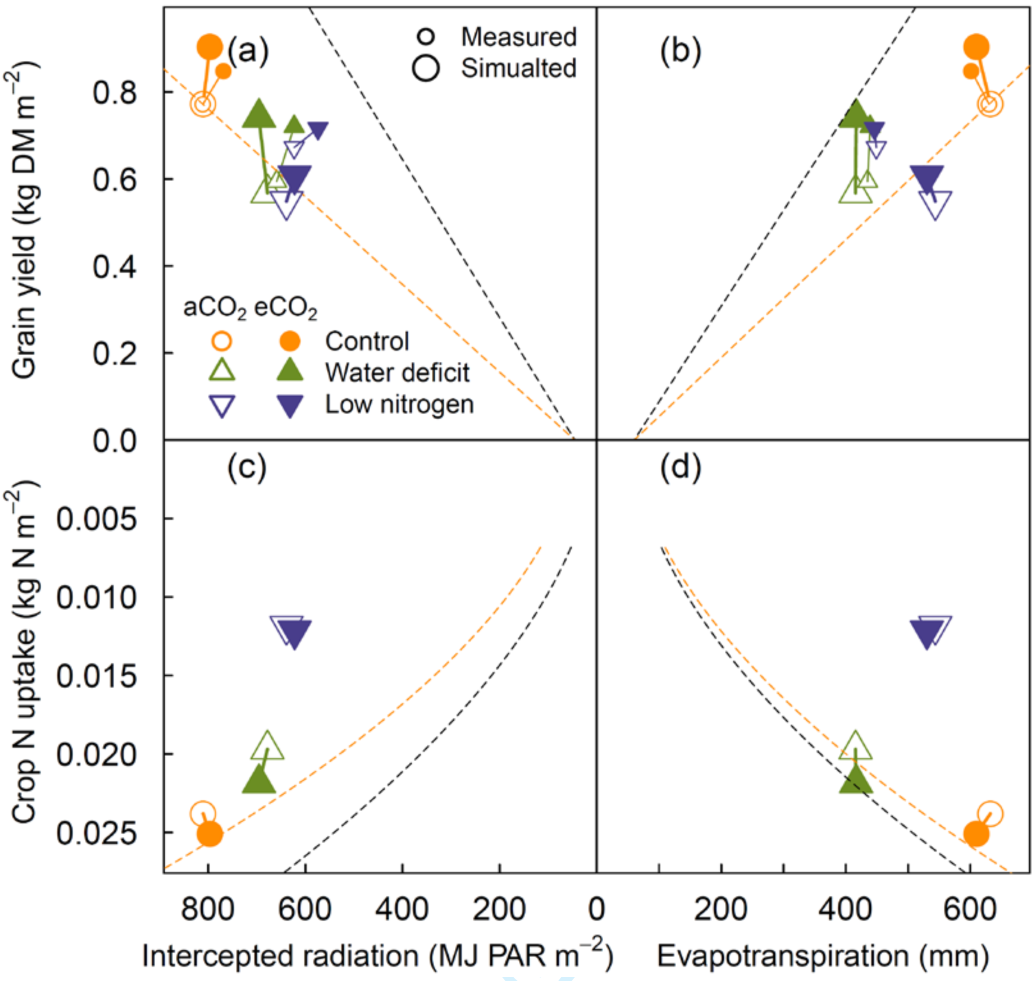

Figure 2. Effect of nitrogen supply, water supply, and atmospheric CO_2 concentration on resource use efficiency and trade-offs illustrating the identity in Figure 1a. A Free air CO_2 enrichment experiment conducted over a four years period with a spring wheat cultivar at Maricopa, AZ, USA (Kimball *et al*., 2017) was simulated with the wheat simulation model *SiriusQuality* (Martre *et al*., 2006; Martre and Dambreville, 2018). In the first two years wheat crops were grown with high (38.9 g N m^{-2}) and low (7.6 g N m^{-2}) nitrogen supply under ambient (370 ppm; aCO_2) and elevated (550 ppm ; eCO_2) atmospheric CO_2 concentration. In the following two years a fully irrigated (665 mm) and a water deficit (330 mm) treatments were factorized with the same two CO_2 treatments. In (a) and (b), black dashed lines are upper limits of grain yield calculated with potential radiation use efficiency (2.93 g above ground DM MJ^{-1} PAR; Sinclair and Muchow, 1999), harvest index (0.6; Foulkes *et al*., 2011), and water use efficiency (2.2 g grain DM m^{-2} mm^{-1}; Sadras and Angus, 2006) for wheat, and orange dashed lines are RUE and WUE isopleths calculated with measured data for the control treatment, respectively. In (c) and (d), dashed lines are critical crop N uptake defined as the minimum N uptake for achieving maximum above ground biomass calculated using the RUE and WUE shown in (a) and (b) and the N dilution curve for wheat (Justes *et al*., 1994). The solid lines between eCO_2 and aCO_2 are drawn to improve the reading of the figure.

The upper part of Figure 2 shows measured and simulated resource utilisation for radiation (Figure 2a) and water (Figure 2b) when quantified as intercepted PAR or evapotranspiration against crop grain yield. The black dotted lines shows the theoretical potential RUE and WUE and the orange dashed line shows these utilisation efficiencies for the control treatment in ambient CO_2 and with ample water and nitrogen supplies. Points above the orange lines mean that utilisation efficiency is increased relative to control and *vice versa*. Points above the black lines would be above the theoretical resource efficiencies and would therefore be suspicious. Under ambient CO_2, simulations agreed reasonably well with the field measurements but the model underestimated RUE and WUE under water deficit. A higher CO_2 concentration increased both utilisation efficiencies. The model simulated well the effect of elevated CO_2 on RUE but it overestimated the effect of elevated CO_2 on WUE (+23% vs. +14%). Terms 3 and 4 in Figure 1a, which measure the trade-offs between N, radiation, and evapotranspiration, are shown in the lower part of Figure 2. The dashed lines show critical N uptake (that is, the minimum crop N uptake for achieving maximum above ground biomass) considering the theoretical potential utilisation efficiencies (black lines) and those for the control treatments (orange lines). For the control and the water deficit treatment, crop N was close to the critical N uptake, especially under elevated CO_2. The increase of crop N uptake under elevated CO_2 is consistent with the reported higher crop N demand under elevated CO_2 (Rogers *et al*., 2006). Points for the low N treatment were significantly above the critical N uptake curve, showing that N uptake relative to radiation and water use was significantly reduced in real and simulated crop growth.

Our conclusions from this very preliminary analysis using a single crop model are that models should be examined for their ability to represent resource use efficiencies under ambient and elevated CO_2 concentrations and, more importantly, how models portray the trade-offs between resources. The upper part of Figure 2 can also be used to estimate resource co-limitation if the upper-limit of resource utilization efficiency can be defined (Cossani *et al*., 2010). Theory developed in ecology predicts that plant growth is maximized when all resources are equally non-limiting (Sperfeld, 2016) and several experimental and modelling studies have shown that crop yield is often co-limited by water and N (Cossani and Sadras, 2018), and theory from ecology have been introduced in agricultural science and can provide a theoretical framework to test model consistency and help understanding uncertainties when crop models are used in IAMs studies such as those used recently in the IPCC. The identity used here as an illustration of the proposed approach can be easily modified to account for N utilization efficiency and other identities can be worked out (including abiotic factors) to fit the aim of a study. Such work cannot be solely model-based but requires the analysis of existing experiments and where necessary the making of new experiments to test our models. Such experiments are rare, partly because experiments are often designed in the absence of clear theoretical deductive analysis. For example, even in the very comprehensive Maricopa FACE experiment used here, an emphasis on the interactions between water and N resource utilisation efficiencies would have resulted in parallel measurement of N as well as water uptake, while only water uptake was measured.

6.2. | Impacts, adaptation and mitigation in integrated assessment studies

Our second point to improve future impacts and assessments analyses concerns how impacts, adaptation and mitigation have historically been assessed by different communities using different methods. This history is reflected in the structure of the IPCC reports, with each of these, especially mitigation, being treated separately. This separation has also been reflected in many policy domains. Recent progress and trends have helped to break down these silos. One example of this is climate-smart agriculture. This idea was borne from the need to integrate climate adaptation and mitigation. Early progress in climate-smart agriculture came through intellectual and political leadership (Lipper *et al*., 2014), with the evidence base supporting the identification of specific climate-smart agriculture practices coming later (e.g. Rosenzweig *et al*., 2016). Similarly, introduction of carbon taxes, carbon prices or greenhouse gas footprint labelling and similar programs necessitates re-evaluation of risk and returns in all components of food systems which could include addressing the implications of increasingly frequent disruptions from climate extremes (Lim Camacho *et al*. 2017).

IAMs are one way of assessing the integration of adaptation and mitigation. Efforts to include agriculture in IAMs is relatively new and a number of challenges need to be addressed (Ewert *et al*., 2015). Whilst crop models are generally responsive to climate, the range of crops that can be simulated is not sufficiently broad for a full assessment of food security. Further, disparities between IAMs and crop models in spatial scale, treatment of uncertainty, data demand and representation of agricultural management all limit the extent of crop model integration into IAMs that is currently possible. Whilst significant progress is being made with these challenges (Ruane *et al*., 2017), it is likely that more than one approach is needed if we are to capture the range of trade-offs and synergies that are important to food systems (Vermeulen *et al*., 2013) and relevant to policy design and development in the huge variety of contexts that exist globally. One particularly important challenge, for any holistic approach to food systems and climate change, is to develop a framing for research that recognises that emissions occur across the full range of activities that deliver food security, not only agricultural production (Whitfield *et al*., 2018). Thus the idea of climate-smart food systems has emerged as way to take a more comprehensive look at how climate, food and human activities are interrelated.

Progress in climate-smart food systems can be expected to come from a number of promising avenues. IAMs have the potential to be an important tool for allowing a broader and more complete view of agricultural impacts, adaptation and mitigation but as argued earlier, can be limited in their ability to include locally-important factors. Risk assessment methods provide another set of approaches (Challinor *et al*., 2018a). Working with stakeholders and using multiple methods to identify the timing of key risks is one approach that has been shown to work within constrained systems (Challinor *et al*., 2016) but is not without its costs and risks (Cvitanovic *et al*. 2019). The review of Challinor *et al*. (2018b) found increasing transparency and inter-comparability in risk assessments to be an important aspect to future work. While studies often address uncertainty, the nature of the treatment and the assumptions underlying that analysis are often unclear. Paraphrasing ESM3 from Wesselink *et al*. (2015), we can list some sources of this lack of clarity: the question of whether and how observations been used, and if so whether measurement uncertainty been accounted for; which uncertainties in model inputs (e.g. initial conditions, boundary conditions, physical constants, driving variables) and model structure (e.g. inaccuracy in model equations, spatial and temporal discretization) have been assessed?; have intrinsic and non-measurable stochastic variability (e.g. fundamental limits to predictability resulting from chaotic processes) and uncertainty resulting from explicit variation of model parameters (i.e. potential over- or under- estimation of uncertainty when producing a perturbed-parameter ensemble) been assessed? Uncertainty also arises from insufficient ensemble size (i.e. potential under-estimation of uncertainty due to not capturing the full range of possible model responses) and the use (or not) of expert judgement.

Whitfield at al. (2018) set out an agenda for climate-smart food systems research, arguing that a number of fundamental questions need to be answered, including: what is climate smartness and how do we measure it?; what trade-offs emerge from climate-smart practices?; how do theory-based climate-smart actions differ across spatial scales?; which climate-smart actions are feasible and attractive?; in which systems and at which scales is climate smartness evident?; and finally, how can diet choices contribute to the climate smartness of the food system in the long term?

Issues of spatial scale play a key role in agriculture and climate change, as highlighted by Whitfield *et al*. (2018) for climate-smart food systems, and by many authors for the narrow and older field of crop-climate modelling (Hansen and Jones, 2000; van Bussel *et al*., 2011, Challinor *et al*., 2015). Food systems cross international boundaries and recent work has highlighted how climate risks cross both sectors and international boundaries. Challinor *et al*., (2018b) and The Royal Society (2017) concluded that complex risk transmission mechanisms of this sort cannot be assessed using existing impacts, adaptation and mitigation research alone. Rather, a range of approaches are needed, including expert judgement, interactive scenario building, global systems science, innovative use of climate and integrated assessment models, and methods to understand societal responses to climate risk (Figure 3). These are the types of issues and approaches addressed by policy design and development groups in government and in industry and there is likely much to learn from them in relation to developing effective climate-smart food systems: integrating policy, practice and research.

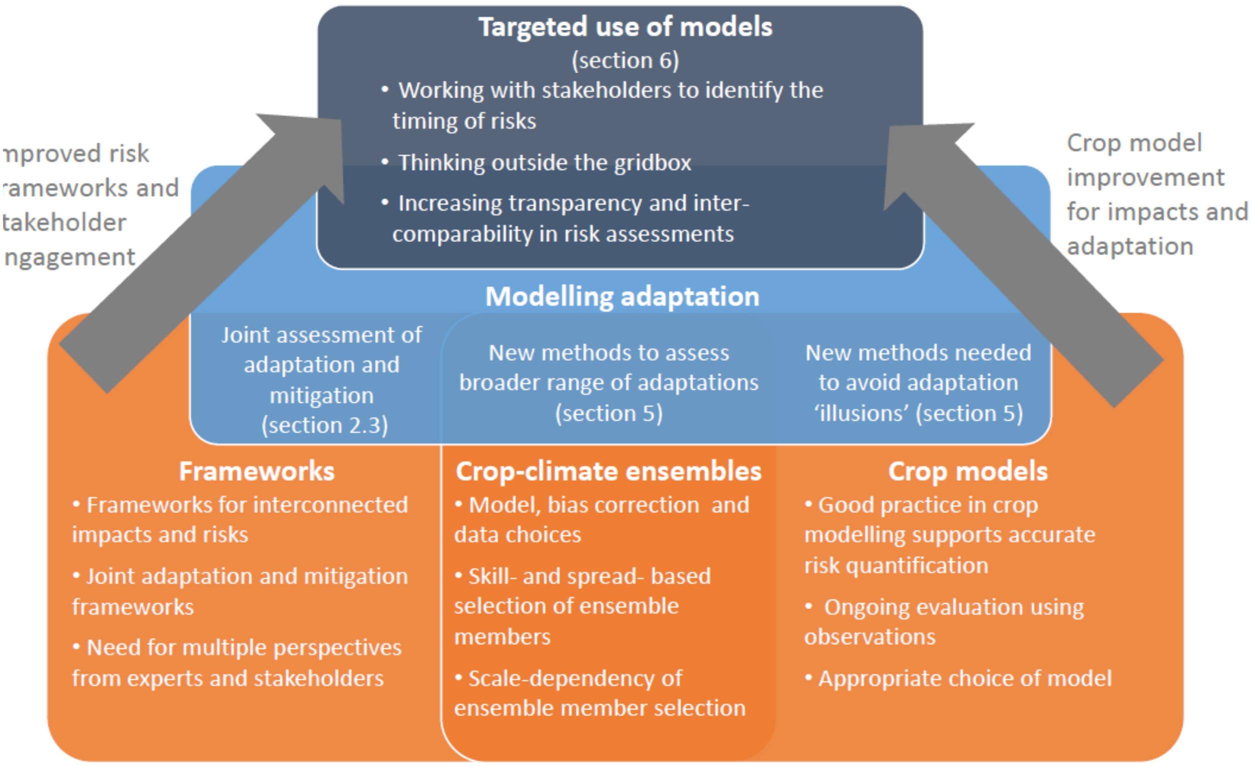

Figure 3. The range of approaches that are needed, including expert judgement, interactive scenario building, global systems science, innovative use of climate and integrated assessment models, and methods to understand, project societal responses to climate risks.

7 | Conclusion

The IPCC ARs have evolved over 34 years since AR1. During this time, several themes have become apparent, which we have tried to identify in this review. There has been a plethora of modelling studies on the impacts, with and without adaptation, on a wide range of crops and in many regions. Results from these more than 2100 studies show consistently both the adverse effect of climate change on a basic element of food security, namely food production and the significant potential value of adaptation in reducing these impacts. Over the IPCC cycles, an increasing array of mitigation approaches has been treated by both top-down and bottom-up approaches and the range of adaptation options considered has both become more nuanced and broader. These are positive evolutions in the synthesis and evaluation of research that is the role of the IPCC authors and reviewers. However, there are large remaining gaps – particularly with respect to impacts, adaptation and mitigation in the livestock sector. The lack of quantitative data on livestock in the five ARs was a shock for us as ‘historical’ reviewers which needs addressing as does an increased attention to non-production aspects of food systems. We also suggest a couple of ‘closer to now’ issues on the interactions between resource use efficiencies and the future role of IAMs that may become important in the context of climate change assessment in the near term. In the longer term, future directions for research in agriculture and food will be to ask as much about efficiency and food demand issues as the past has been concerned with adequacy of food supply and environmental outcomes. Thus, issues such as human nutrition and health, diet and obesity, food waste, circular and local food systems could become dominant themes for food systems research and thereby the foci for future IPCC Assessment Reports.

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