Agriculture in a changing climate: Keeping our cool in the face of the hothouse

Philip Thornton1,2, Dhanush Dinesh1,3, Laura Cramer1,3, Ana Maria Loboguerrero1,3 and Bruce Campbell1,3,4

Abstract
The challenges facing agriculture in the coming decades are daunting. Recent research suggests that the impacts of climate change on agriculture and food systems may be wider-ranging than previously understood. Can feasible pathways to a food secure and sustainable future be identified? The scale of change required to meet the sustainable development goals, including those of no poverty, zero hunger and the urgent action needed to address climate change, will necessitate the transformation of local and global food systems. We identify eight elements of a theory of change to drive such transformation and highlight four pathways by which transformation may occur. We conclude with some suggestions for ‘business unusual’ for agricultural research for development.

Keywords
transformation, adaptation, food systems, research for development, sustainable development goals

Introduction
The heart of the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, is the 17 sustainable development goals (SDGs; United Nations, 2015). These call for urgent action by all countries to end poverty and hunger, improve health and education, reduce inequality and spur economic growth, while at the same time tackling climate change and working to preserve the planet’s natural resources. In addition to trying to achieve the SDGs, by the middle of the century, agricultural production will need to increase substantially to feed growing and urbanizing populations, particularly in sub-Saharan Africa (SSA) and South Asia. Estimates of the production increases needed vary, depending on assumptions about future efficiency and consumption pattern changes, but range from 25% to 70% (Alexandratos and Bruinsma, 2012; Hunter et al., 2017).

Smallholder agriculture will remain crucial for sustainable development and achieving several of the SDGs (Herrero et al., 2017), at least in the short to medium term. At present, 30% of many food commodities in Africa and Asia are produced on farms of less than 2 ha in size, and 60–75% is produced on farms of less than 20 ha (Herrero et al., 2017, Ricciardi et al. 2018). Although widespread intensification of production is urgently needed in SSA and elsewhere, smallholders will still form the key target group for agricultural research for the development for the foreseeable future (Masters et al., 2013). This means that agricultural research for development will have to work collectively with the great majority of the more than 600 million smallholders who will be farming in 2030 (Campbell and Thornton, 2014) if agricultural production is to be sustainably intensified and the estimated global population of 8.5 billion fed (UNPD, 2015). Altogether, more than 2.5 billion people make their living from the agriculture sector (FAO, 2012). For the great majority in developing countries, their livelihoods are on the front line of climate change.

In this ‘perspectives’ piece, we briefly consider the scale of the agriculture challenge in the Anthropocene (a proposed epoch dating from the commencement of significant human impact on the Earth’s geology and ecosystems). The challenge is daunting, but can feasible pathways to a food secure and sustainable future be identified? First, we highlight some recent science on the impacts of climate change on agriculture and food systems, which is adding to the challenge. We then undertake a quick stocktake of where
we are in relation to the future food production challenge. We then consider where food systems need to be in 2030, the year by which the SDGs should be achieved, and some of the actions that may help us get there. We conclude with some comments on the agricultural research for development agenda in the next decade.

**Climate change: The challenges facing agriculture are mounting**

Climate trends over the last several decades have already been affecting agriculture. For example, these effects have been negative with respect to wheat and maize production in many regions (Porter et al., 2014), although warming has benefitted crop production in some high-latitude regions. For the future, climate projections indicate that agricultural production will be affected through multiple pathways: heat stress via temperature increases; more frequent extreme weather events such as droughts and floods; changing rainfall amounts and patterns; shifts in timing and length of growing seasons; and changing prevalence and severity of pests, weeds and crop and livestock diseases, for example. There is an enormous literature on these projected impacts, regularly summarized in the IPCC’s series of Assessment Reports and elsewhere. In general, strong negative effects of climate change are expected for major crops, especially at low latitudes. Exceeding critical physiological limits in temperature will sharply reduce grain yields. Rainfall impacts on agriculture are generally uncertain (Lobell and Asseng, 2017), and changes in variability in climate and extreme events may affect food security in ways not yet fully elucidated (DeVries, 2018; Thornton et al., 2014).

Nevertheless, changes in climates over the last 30 years have already reduced global agricultural production in the range of 1–5% per decade globally, compared with what would have been achieved in their absence, with particularly negative effects for tropical cereal crops such as maize and rice (Porter et al., 2014). The evidence is mounting that even at low (+2°C) levels of warming, agricultural productivity is likely to decline across the globe but particularly across tropical areas (Challinor et al., 2014). At +1.5°C of warming, impacts on human and natural systems will still be considerable (IPCC, 2018). Impacts will be felt on all agricultural systems. Temperature shifts are likely to change the distribution and productivity of major cash crops such as coffee and cocoa in some tropical regions (Schroth et al., 2016). Climate change impacts in livestock systems and fisheries are less well-studied, although projections indicate substantial reductions in forage availability in some regions, and widespread negative impacts on forage quality and thus on livestock productivity, with cascading impacts on incomes and food security. With respect to fisheries, a decline is projected between 5% and 10% by 2050 on fish catch in tropical marine ecosystems (Barange et al., 2014). Shifts in suitable habitats will also affect the distribution of fish and plankton (Brander, 2010).

The science is accumulating that there are other, more indirect effects of climate change on agriculture and food systems. Rising atmospheric concentrations of carbon dioxide (CO₂) have long been known to have a beneficial effect on the growth of many food crops such as wheat, rice, barley and potatoes that follow the C3 photosynthesis pathway. At the same time, such crops produce more carbohydrates at the expense of other nutrients such as protein, iron (Fe) and zinc. Davis et al. (2004) found declines in protein, calcium, phosphorus, Fe, riboflavin and ascorbic acid for 43 food groups between 1950 and 1999. This can partially be attributed to widespread use of higher yielding crop varieties that inadvertently trade-off nutrient content, but the role of rising CO₂ concentrations has recently been highlighted. Analysis by Smith and Myers (2018) of the effects of elevated CO₂ concentrations in 2050 on the sufficiency of dietary intake of Fe, zinc and protein in 151 countries suggests that an additional 175 million people will be zinc deficient and an additional 122 million people will be protein deficient. South and Southeast Asia, Africa and the Middle East are the regions most at risk. Similar effects on forage quality have been found in forages (Augustine et al., 2018). About 57% of grasses globally are C3 plants (Osborne et al., 2014) and thus susceptible to CO₂ effects on their nutritional quality. These impacts will result in greater nutritional stress in grazing animals as well as reduced meat and milk production, with many knock-on effects on those households that are dependent on livestock for some or all of their livelihoods.

Climate change is already having impacts on human health issues, and these are worse than previously understood (Watts et al., 2017). These include the effects of higher temperatures on the capacity of people to work in the fields, with major implications for livelihoods based on non-mechanized farming. Globally, rural labour capacity fell by more than 5% between 2000 and 2016 (Watts et al., 2015). There is high spatial variability in many human health impacts, however. The nearly 10% increase since 1950 in vectorial capacity of the mosquito that carries dengue fever has occurred predominantly in lower- and middle-income countries, and India has been disproportionately affected by an additional 125 million worldwide exposure events – measured by the number of people over age 65 experiencing a potentially fatal heat wave – since 2000 (Watts et al., 2017). At the same time, the areas of the world with the highest vulnerability to undernutrition are also those where crop yield losses due to climate change are projected to be among the highest (Watts et al., 2017).

Because climate change interacts with the climate’s natural variability across time scales, farmers worldwide experience climate change not only as a gradual change in temperature and rainfall but also as increasing frequency and intensity of extreme weather events that are harder to prepare for. While there is growing evidence that the risk of extreme events will increase in the future in much of the developing world, the ways in which these risks will manifest themselves and affect agricultural systems are not that clear (Thornton et al., 2014). Increasing climate variability and extremes have been identified as one of the key drivers behind the recent rise in global hunger and a leading cause of severe food crises (FAO, 2018), affecting both crop and livestock systems. Forage production and animal stocking...
rates can be significantly affected by drought intensities and durations as well as by long-term climate trends. After a drought event, herd size recovery times in semi-arid rangelands may span years to decades in the absence of proactive restocking through animal purchases, for example (Godde et al., 2018). Indeed, increasing climate variability may threaten the long-term viability of agriculture-based livelihoods in many places. There is increasing evidence of the role of environmental factors in influencing migration flows, and this influence is expected to increase as climate change impacts intensify, particularly in highly vulnerable regions (Falco et al., 2018).

Are we on track to meet the future food production challenge?

Overall, there has been considerable progress in reducing rates of undernourishment and improving levels of nutrition and health, although substantial regional differences exist. But the last 3 years have seen a rise in world hunger after a prolonged decline (FAO, 2018). An estimated 821 million people (one in every nine) are undernourished, and 2 billion suffer micronutrient deficiencies. Undernourishment and severe food insecurity is increasing in almost all regions of Africa as well as in South America. FAO (2018) lay some of the blame for this on increased climate variability, and there seems little doubt that both short- and long-term climate change may undermine recent progress made on SDGs. Under business as usual, without additional efforts to promote pro-poor development, more than 650 million people would still be undernourished in 2030. Even where poverty has been reduced, pervasive inequalities remain, hindering poverty eradication.

The current status of adaptation globally, nationally and locally is difficult to assess. Adaptation monitoring and evaluation (M&E) is increasingly being seen as a vital component in the process of adapting to climate change; in this way, countries can increase their understanding of climate risks, increase the effectiveness of adaptation measures and increase their accountability under the United Nations Framework Convention on Climate Change (Vallejo, 2017). But globally comparable metrics that track progress towards global goals on adaptation based on country-level information, while avoiding undue burden on countries, pose considerable challenges (UNEP, 2017). These include the country-specific nature of the adaptation M&E systems used, which may measure different aspects of adaptation. In addition, many M&E systems focus predominantly on process or output-based information, which are generally insufficient for measuring progress towards global goals. At the same time, there are no generic ‘off the shelf’ methodologies that can be used to assess adaptation outcomes. There is already a large and growing literature around the metrics that may be used (e.g. Braimoh et al., 2016; Chaudhary et al., 2018; FAO, 2017; Hills et al., 2015), but the development of a ‘minimum metric set’ that can be used across a wide range of situations, although greatly needed, has so far proved elusive.

Nevertheless, we do have some evidence that adaptation may not be on track. For example, at the global level, crop yield growth rates per year are lagging behind. A recent meta-analysis of integrated assessment model projections to the 2050s indicates that on average, a crop yield growth rate of 1.8% per year will be needed to feed the global population; the current crop yield growth rate is 1.2% per year (Aggarwal et al., 2018). This is clearly of concern for vulnerable lower- and middle-income countries with high population growth rates and a food self-sufficiency agenda. On the other hand, international trade can play an important role in extenuating adverse impacts of climate change on food security, as the comparative advantage of different countries and production regions change (Baldos and Hertel, 2015). Barriers to trade may limit this role in some situations, however, and agricultural trade liberalization may undermine global mitigation gains (Himics et al., 2018).

At the local level, there have undoubtedly been some successes for smallholders adopting interventions to increase their resilience. Many of these are ‘no regret’ options – alternatives that are viable and beneficial regardless of uncertain future climatic conditions. There are many examples for both crops and livestock that fall into such a category, focusing on adaptability to varying climate and extreme events (Dinesh et al., 2017). For crops, breeding to develop cultivars with traits for adaptability, enhanced nutrient quality and resilience to varying temperature and precipitation could contribute substantially to future food security, as well as resistance to pests and diseases. In mixed systems, increased integration between the crop and livestock enterprises can play a similar role in contributing to food security under a range of different climatic conditions, for example.

There are many challenges to the scaling up successful pilots (Westermann et al., 2018). So while climate smart interventions exist, there is only limited evidence of the overall progress in uptake in the last decade. For instance, household surveys conducted by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) in 21 lower- and middle-income countries found only limited evidence of smallholder farming changes at the scale needed to adapt to climate change and enhance food security of significant proportions of the population. On average, more than 13% of the households surveyed across five regions of the world were food insecure, with more than five hunger months per year, and only 16% were intensifying production in some way (Thornton et al., 2018).

Recent literature suggests a growing recognition that incremental adaptation may be inadequate to deal with rapid shifts and tipping points for food production under global change in many developing countries. Indeed, there may be limits to what incremental adaptation can achieve for the poorest smallholders, particularly in East and West Africa (Ritzema et al., 2017). Major, non-marginal transitions in agriculture (or transformative changes) are needed, although there are many issues associated with transformation related to the enabling environment, financing and
equity, for example (Blythe et al., 2018; Vermeulen et al., 2018).

Where do we need to be by 2030?

With only a dozen rainfed harvests left until 2030, food systems will need to transform radically, if the SDGs are to be even partially attained (Loboguerrero et al., 2018). Campbell et al. (2018) have put forward a theory of change to drive transformation and achieve the SDGs, with eight key elements. Using these as the basis, below we identify likely outcomes that need to be achieved under each element by 2030 to realize a transformation.

Enhanced investment flows, private sector activity and public–private partnerships. Current levels of investment in climate action in agriculture will be insufficient to drive sectoral transformation (Sadler et al., 2016). In 2015/2016, agriculture, forestry, land use and natural resource management received only US$7 billion of the total public climate finance of US$141 billion (Buchner et al., 2017). Innovative approaches to enhance investment flows need to be put in place, and these could include increasing private sector finance, impact investing and blended finance (Loboguerrero et al., 2018). Enhanced investment flows can also be a result of more effective public investment in agriculture to generate climate co-benefits, for example, by increasing the degree of climate smartness of the more than US$600 billion in public agriculture support received by farmers every year (OECD, 2018).

Increased availability and uptake of credit and insurance. In addition to more and better directed financing, other economic incentives can also drive transformation in the sector. For example, index-based agricultural insurance, an innovation that triggers payouts based on an index (e.g. rainfall or sampled yields) correlated with agricultural losses, rather than actual losses, can help protect farmers’ productive assets in the face of extreme climate events and promote farmers’ livelihoods by overcoming barriers to adoption of improved technologies and access to credit and market opportunities. In the face of growing climate risks, well-designed index insurance embedded in comprehensive agriculture risk management approaches needs to be in place. There has been progress: some 650,000 farmers in Africa now have access to insurance (Hazzel and Hess, 2017), but that is still very limited coverage, given more than 40 million smallholdings in SSA alone (Lowder et al., 2016). In addition to insurance, extension of credit to farmers to adopt climate-resilient technologies and practices will also be a key.

Strengthened and well-networked local organizations. For food systems transformation to be successful, it will need to be led by farmers and consumers (Loboguerrero et al., 2018). Efforts thus need to be put in place to strengthen farmer and consumer organizations and their networking. One example is Wefarm (wefarm.org), a farmer-to-farmer digital network with more than a million users across Kenya and Uganda, which can be accessed via Internet or through text messaging on a mobile phone. Such bottom-up and multi-level approaches can help drive more effective implementation and scale up successful actions (Ostrom, 2010).

Scaled out climate-informed advisories and early warning. Use of climate information in decision-making is not new, but improving the quality and reach of climate information services can greatly enhance the adaptive capacity of smallholder farmers and enable better decisions. For example, in Senegal, seasonal forecasts are now transmitted nationwide through 82 rural community radio stations and SMS, potentially reaching 7.4 million rural people (CCAFS, 2015). Such efforts need to be scaled out with greater collaboration between agricultural sector actors, meteorological services and media.

Realizing the digital era in food systems. Agriculture and allied sectors have lagged behind in the use of information and communication technologies (ICTs) (WEF, 2018). This needs to change and the digital era in food systems needs to be realized to accelerate food systems transformation. Such a shift will be characterized by interaction between food systems players, which improves efficiencies, reduces costs and enables better decisions. For example, the World Economic Forum estimates that if around 275–350 million farms gain access to mobile-based services by 2030, the total additional income generated would be US$100–200 billion driven by production increase and avoided losses (WEF, 2018). Such changes are emerging; for example, in Colombia, rice farmers saved US$1.7 million in 2014, following advice based on big data analysis, done by researchers at the International Centre for Tropical Agriculture (Loboguerrero et al., 2018). Scaling up such best practices and improving extension services through ICT tools can help transform the sector.

Scaled out climate-resilient and low-emission practices and technologies. Adoption of climate-resilient and low-emission practices and technologies in agriculture is still not at desirable levels. It has been estimated that current technologies and practices only deliver 21–40% of the emission reductions needed in agriculture to meet the Paris climate agreement goal of limiting global warming to 2°C (Wollenberg et al., 2016). If agriculture is to deliver its share in realizing the Paris climate agreement goals and the SDGs, climate-resilient and low-emission practices and technologies will need to be scaled up.

Taking into account of different contexts for targeting interventions. Communities dependent on agricultural and coastal livelihoods are disproportionately affected by the impacts of climate change (IPCC, 2018). However, agricultural systems are diverse and differentiated, with a wide range of different motivations and reasons that drive decisions. Moreover, factors including cultural identities, incentives, technologies, subsidies and sanctions also affect agricultural livelihoods. This means that efforts to transform food systems should not only endeavour to target the
most vulnerable farming communities but also take into account context-specific differences which are key to successful implementation. Intracommunity heterogeneity also needs to be evaluated, with issues such as gender inequality, socioeconomic differentiation, access to land and other characteristics being taken into consideration.

Enhancing capacity and promoting policies and institutions that enable change. A conducive-enabling environment which encourages innovation and action needs to be in place to drive action by farmers, businesses, researchers and investors. Key enablers for such an enabling environment would include the right mix of policies (agriculture as well as other sectors) and incentives. These policy frameworks and incentives will need to be complemented by efforts to enhance capacity at various levels for effective implementation.

Pathways towards the SDGs

The theory of change proposed by Campbell et al. (2018) encompasses different pathways to progress towards the SDGs. Concerted action will be needed on a huge scale, involving four crucial elements.

Next generation technologies likely to drive transformation

Next generation technologies driven by the fourth industrial revolution are driving transformation in other sectors, and there is an opportunity to realize such a transformation in food systems. At the production end, developments including artificial meat (Bonny et al., 2015), nitrogen fixation in cereals (de Bruijn, 2015), reconfiguring plant photosynthesis to increase its efficiency (Furbank et al., 2015) and asexual reproduction in staple food crops are some of the next generation technologies likely to transform food production as we know it today. Advances in services to support production, including big data analytics, artificial intelligence and machine learning and advanced robotics, can change the way production is planned and executed. In terms of food supply chains and marketing, technologies which promote information gathering and sharing will improve efficiencies and better address the needs of consumers. Application of next generation technologies pertaining to consumption, for example, to optimize diets, is also likely to change the demand for food products. Technological change and its effects are notoriously difficult to predict; although a degree of technological optimism is appropriate (e.g. Voegele, 2018), this needs to be tempered by no-regrets pragmatism.

Policy and governance

Current policy frameworks, including nationally determined contributions under the Paris climate agreement and the growing number of climate-smart agriculture policies and programmes, create a favourable enabling environment for climate action in the sector. For a sectoral transformation to occur, the implementation of these policies should be expedited with emphasis on effective governance mechanisms. Focus should also be placed on cross-sectoral coordination, as much of the incentive for climate action in agriculture will come from other sectors such as energy, finance and ICT, for example.

Mechanisms to address food loss and waste

A third of all food produced (around 1.3 billion tons) is lost or wasted every year, with loss in the beginning of the food supply chain mostly occurring in developing countries and waste at the consumer end of the chain being the main issue in developed economies (FAO, 2011). Addressing this inefficiency in the food system has the potential to deliver on multiple SDGs. For developing countries, this requires considerable investment to develop infrastructure in producer areas to prevent losses, awareness raising and information gathering to track and manage food loss and waste. Such efforts make economic sense; currently food waste costs over US$400 billion per year, and this is projected to increase to US$600 billion within 15 years (WRAP, 2015). Reducing consumer food waste by 20–50% in 2030 would already result in savings of US$120–300 billion a year (WRAP, 2015) and help tackle the nearly 7% greenhouse gas emissions which emanate from food loss and waste.

Mechanisms to drive dietary changes

While hunger and undernutrition are key issues in many parts of the world, overconsumption is leading to increase in obesity and non-communicable diseases such as diabetes. To a large extent, this reflects inefficiencies in the food system, whereby increasing production under climate change does not provide the necessary nutrition to a growing population. Addressing these inefficiencies can deliver positive outcomes for both the climate and nutrition. Dietary shifts towards more sustainable and nutritious choices require action at multiple scales; at the policy level, actions are needed to shift the focus from economic growth in conventional terms to an emphasis on well-being and sustainability. Such a shift also needs to be reflected in prevailing business models and awareness raising and incentives at the individual level.

How can agricultural research for development contribute?

The challenge is immense, and the time available is short. What does the agricultural research for development community need to do over the next 12 years? That it has to be ‘business unusual’ is obvious, and this may include the following:

- Understand more broadly how and where agriculture fits, both sectorally and geographically, and rethinking its relationship with food systems. This highlights the need for rigorous, climate-informed
priority setting, to allow a concentration on the agricultural technologies and practices that are resilient in the face of 2°C of warming. This should be coupled with high-resolution targeting so that different technologies and practices can be set within appropriate local contexts.

- Make early decisions concerning whether we have the food and feed crop varieties that will maintain and even enhance productivity in a warmer, more climate-variable future; if there are other traits that need to be incorporated into breeding programmes, support, develop and implement mechanisms for fast tracking these.

- Make much better use of the ‘back catalogue’ of over 60 years of work on agricultural research for development in many lower income countries, especially in Africa. This includes the work of many national and regional programmes, as well as CGIAR and other international public organizations. Fast tracking the completion and utilization of compendia of the interventions that we know work where and why, from decades of field work in different regions, should be a priority.

- Pick some likely early winners in the transformative technology stakes; these would include relatively low-tech options such as alternative protein sources for humans and animals and new food storage technologies such as those based on biodegradable and microorganism coatings. Leave the private sector to pick up higher cost, higher tech (and ultimately more disruptive) options such as reconfiguring photosynthesis for greatly increased efficiency and nitrogen-fixing cereals.

- Understand more about the synergies and (particularly) the trade-offs that specific adaptation and mitigation decisions may bring about: between food system dimensions (Béné et al., 2019) and between the SDGs themselves (Campbell et al., 2018; Nilsson et al., 2016). Navigating these successfully will depend to a great extent on strengthening the effectiveness of and incentive structures for multidisciplinary and transdisciplinary teams and innovative partnership models that develop and implement highly attractive business cases with the private sector supported by national and international climate finance.

- Understand and adapt to the emerging innovation landscape by strengthening the directionality of transformation towards sustainable development through new value networks and governance, participating in the broad-based collaborations that will increasingly be needed to drive food system innovation and addressing the many social license issues that will increasingly arise as a result of new technology (Hall and Dijkman, 2018).

The window of opportunity for action on the SDGs is clear. For serious, concentrated action on climate change, this window is forever shrinking. We know that even a +1.5°C world will erode many of the advances that have been made in recent decades on food security and poverty reduction (IPCC, 2018). There are prospects for the planet that are much more dire: self-reinforcing feedbacks in the earth system that could cause continued warming on a ‘Hothouse Earth’ pathway, even as human emissions are reduced (Steffen et al., 2018). The impacts on and disruptions to food systems, societies and economies do not bear thinking about. Unless we collectively redouble the efforts to curb CO2 emissions and lower the emissions trajectory, agriculture will struggle to cope.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by CGIAR Fund Donors and through bilateral funding agreements as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security. For details please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of these organizations.

**References**

Aggarwal P, Vyas S, Thornton PK, et al. (2018) How much does climate change add to the challenge of feeding the planet this century? Environmental Research Letters (submitted).

Alexandratos N and Bruinsma J (2012) World Agriculture Towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations. ESA Working Paper no. 12–03.

Augustine D, Blumenthal D, Springer T, et al. (2018) Elevated CO2 induces substantial and persistent declines in forage quality irrespective of warming in mixed grass prairie. Ecological Applications 28(3): 721–735.

Baldos ULC and Hertel TW (2015) The role of international trade in managing food security risks from climate change. Food Security 7(2): 275–290.

Barange M, Merino G, Blanchard JL, et al. (2014) Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change 4: 211–216.

Béné C, Oosterveer P, Lamotte L, et al. (2019) When food systems meet sustainability – Current narratives and implications for actions. World Development 113: 116–130.

Blythe J, Silver J, Evans L, et al. (2018) The dark side of transformation: latent risks in contemporary sustainability discourse. Antipode. Antipode 55: 1206–1223.

Bonny SP, Gardner GE, Pethick DW, et al. (2015) What is artificial meat and what does it mean for the future of the meat industry? Journal of Integrative Agriculture 14: 255–263.

Braimoh A, Emenanjo I, Rawlins MA, et al. (2016) Climate-Smart Agriculture Indicators. Washington: World Bank.

Brander K (2010) Impacts of climate change on fisheries. Journal of Marine Systems 79: 389–402.

Buchner B, Oliver P, Wang X, et al. (2017) Global Landscape of Climate Finance 2017. Climate Policy Initiative. Available at:...
www.climatepolicyinitiative.org (accessed 12 September 2018).
Campbell B and Thornton P (2014) How Many Farmers in 2030 and How Many Will Adopt Climate Resilient Innovations? Info Note, Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
Campbell B, Hansen J, Rioux J, et al. (2018) Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. Current Opinion in Environmental Sustainability 34: 13–20.
CCAFS (2015) The Impact of Climate Information Services in Senegal. Outcome Case No. 3. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
Challinor AJ, Watson J, Lobell DB, et al. (2014) A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change 4: 287–291.
Clements A, Gustafson D and Mathys A (2018) Multi-indicator sustainability assessment of global food systems. Nature Communications 9: 848.
Davis DR, Epp MD and Riordan HD (2004) Changes in USDA food composition data for 43 garden crops, 1950 to 1999. Journal of the American College of Nutrition 23: 669–682.
de Bruijn FJ (2015) The quest for biological nitrogen fixation in cereals: a perspective and prospective. In: de Bruijn FJ (ed.) Biological Nitrogen Fixation. Hoboken, NJ: John Wiley & Sons, Inc., pp. 1087–1101.
DeVries R (2018) Trade-offs and synergies among climate resilience, human nutrition, and agricultural productivity of cereals – what are the implications for the agricultural research agenda? Background paper for the CGIAR ISPC Science Forum 2018, Available at: https://www.scienceforum2018.org/sites/default/files/2018-09/SF18_background_paper_DeFries_0.pdf (accessed 10 October 2018).
Dinesh D, Campbell BM, Bonilla-Findji O, et al. (2017) 10 best bet innovations for adaptation in agriculture: A Supplement to the UNFCCC NAP Technical Guidelines. Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security.
FAO (2011) Global Food Losses and Food Waste: Extent, Causes and Prevention. Rome: Food and Agriculture Organization of the United Nations.
FAO (2012) Statistical Yearbook. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/017/i3138e/i3138e.pdf (accessed 14 September 2018).
FAO (2017) Tracking Adaptation in Agricultural Sectors. Rome: Food and Agriculture Organization of the United Nations.
FAO (2018) The State of Food Security and Nutrition in the World 2018. Building Climate Resilience for Food Security and Nutrition. Rome: Food and Agriculture Organization of the United Nations.
Falco C, Donzelli F and Olper A (2018) Climate change, agriculture and migration: a survey. Sustainability 10: 1405. DOI: 10.3390/su10051405.
Furbank RT, Quick WP and Siraurl XRR (2015) Improving photosynthesis and yield potential in cereal crops by targeted genetic manipulation: prospects, progress and challenges. Field Crops Research 182: 19–29.
Godde CM, Dizyee K, Ash A, et al. (2018) Climate change and variability impacts on grazing herds: Insights from a system dynamics approach for semi-arid Australian rangelands. Global Change Biology (submitted).
Hall A and Dijkman J (2018). Public Agricultural R&D in an era of transformation. Volume 1 – Analysis and reflections. Rome: CGIAR Independent Science and Partnership Council (ISPC) Secretariat and Commonwealth Scientific and Industrial Research Organisation (CSIRO), pp. 65.
Hassell P and Hess U (2017) Beyond hype: another look at index-based agricultural insurance. In: Pingali P and Feder G (eds) Agriculture and Rural Development in a Globalizing World: Challenges and Opportunities. London: Routledge, pp. 211–226.
Herrero M, Thornton PK, Power B, et al. (2017) Farming and the geography of nutrient production for human consumption. The Lancet Planetary Health 1: 33–42.
Hills T, Pramanova E, Neufeldt H, et al. (2015) A Monitoring Instrument for Resilience. CCAFS Working Paper no. 96. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).
Himics M, Fellmann T, Barreiro-Hurlé J, et al. (2018) Does the current trade liberalization agenda contribute to greenhouse gas emission mitigation in agriculture? Food Policy 76: 120–129.
Hunter MC, Smith RG, Schipanski ME, et al. (2017). Agriculture in 2050: recalibrating targets for sustainable intensification. BioScience 67: 386–391.
IPCC (2018). An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Summary for Policymakers. Geneva: Intergovernmental Panel on Climate Change, Available at: http://report.ipcc.ch/sr15/pdf/ar15_spm_final.pdf (accessed 20 October 2018).
Lobell DB and Asseng S (2017) Comparing estimates of climate change impacts from process-based and statistical crop models. Environmental Research Letters 12: 015001.
Loboguerrero AM, Martinez-Baron D, Birch J, et al. (2018) Feeding the World in a Changing Climate: An Adaptation Roadmap for Agriculture. Rotterdam and Washington: Global Commission on Adaptation.
Lowerw SK, Skoet J and Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Development 87: 16–29.
Masters WA, Djurfeldt AA, De Haan C, et al. (2013) Urbanization and farm size in Asia and Africa: implications for food security and agricultural research. Global Food Security 2: 156–165.
Nilsson M, Griggs D and Visbeck M (2016) Policy: map the interactions between sustainable development goals. Nature News 534(7607): 320.
OECD (2018) Agricultural Policy Monitoring and Evaluation 2018 (Summary). Paris: Organisation for Economic Co-operation and Development.
Osborne CP, Saloman A, Kluiver TA, et al. (2014) A global database of C4 photosynthesis in grasses. New Phytologist 204: 441–446.
Ostrom E (2010) A multi-scale approach to coping with climate change and other collective action problems. Solutions 1: 27–36.

Porter JR, Xie L, Challinor A, et al. (2014) Food security and food production systems. In: Field CB, Barros VR, Dokken DJ, et al. (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge, United Kingdom and New York, USA: CUP, pp. 485–533.

Ricciardi V, Ramankutty N, Mehrabi Z, et al. (2018) How much of the world’s food do smallholders produce? Global Food Security 17: 64–72.

Ritzema RS, Frelat R, Douxchamps S, et al. (2017) Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. Food Security 9: 115–131.

Sadler MP, Millan AA, Swann SA, et al. (2016) Making Climate Finance Work in Agriculture. Washington: World Bank Group.

Schroth G, Läderach P, Martinez-Valle AI, et al. (2016) Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation. Science of the Total Environment 556: 231–241.

Smith MR and Myers SS (2018) Impact of anthropogenic CO2 emissions on global human nutrition. Nature Climate Change 8: 834–839.

Steffen W, Rockström J, Richardson K, et al. (2018) Trajectories of the earth system in the Anthropocene. Proceedings of the National Academy of Sciences 115(33): 8252–8259.

Thornton PK, Ericksen PJ, Herrero M, et al. (2014) Climate variability and vulnerability to climate change: a review. Global Change Biology 20: 3313–3328.

Thornton PK, Kristjanson P, Förch W, et al. (2018) Is agricultural adaptation to global change in lower-income countries on track to meet the future production challenge? Global Environmental Change 52: 37–48.

United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed 10 September 2018).

UNEP (2017) The Adaptation Gap Report 2017. Nairobi: United Nations Environment Programme.

UNPD (2015) The 2015 Revision of World Population Prospects. United Nations Population Division. Available at: https://esa.un.org/unpd/wpp/ (accessed 3 September 2018).

Vallejo L (2017). Insights from National Adaptation Monitoring and Evaluation Systems. Paris: OECD.

Vermeulen S, Dinesh D, Howden M, et al. (2018) Transformation in practice: a systematic review of empirical examples of transformation in agricultural systems under climate change. Frontiers in Sustainable Food Systems 2: 65. DOI: 10.3389/fsufs.2018.00065.

Voegele J (2018) The fourth industrial revolution is changing how we grow, buy and choose what we eat. Available at: https://www.weforum.org/agenda/2018/08/the-fourth-industrial-revolution-is-changing-how-we-grow-buy-and-choose-what-we-eat/ (accessed 3 September 2018).

Watts N, Adger WN, Agnolucci P, et al. (2015) Health and climate change: policy responses to protect public health. The Lancet 386: 1861–1914.

Watts N, Amann M, Ayeb-Karlsson S, et al. (2017) The lancet countdown on health and climate change: from 25 years of inaction to a global transformation for public health. The Lancet 391: 581–630.

WEF (2018) Innovation with a Purpose: The role of Technology Innovation in Accelerating Food Systems Transformation. Geneva: World Economic Forum.

Westermann O, Korner J, Thornton P, et al. (2018) Scaling up agricultural interventions: case studies of climate-smart agriculture. Agricultural Systems 165: 283–292.

Wollenberg E, Richards M, Smith P, et al. (2016) Reducing emissions from agriculture to meet the 2°C target. Global Change Biology 22: 3859–3864.

WRAP (2015) Strategies to Achieve Economic and Environmental Gains by Reducing Food Waste. Banbury: Waste and Resources Action Programme.