IPCC SPECIAL REPORT

FOOD SECURITY

AN IPCC SPECIAL REPORT ON THE IMPACTS OF CLIMATE CHANGE FOR CROP NUTRITION AND CROP YIELD

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SCIENCE & POLITICS OF CLIMATE CHANGE
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Executive Summary

Climate change is affecting all aspects of food security through more severe and frequent weather events including droughts, floods, heat waves, and storms (*very high confidence*).

Elevated CO_2 is a critical variable for determining changes in accumulation of minerals and protein in crop plants under climate change, changing the timing and form of nitrogen assimilation (*high confidence*). Low-rainfall regions are expected to experience lower or more variable grain and protein yields (*low confidence*).

Climate change will result in global yield declines for wheat, maize, and rice (*very high confidence*). This impact presents geographic differences. The most negative consequences are projected among the lower latitude countries, while some high latitude countries can expect increases in yield of certain crops (*very high confidence)*. Regionally, climate change has negatively impacted crop yields in Africa (*very high confidence*). In Southeast Asia, both irrigated paddy and rainfed rice are being affected by climate change (*very high confidence*). In most areas within Southeast Asia, yields are expected to be lower in the future (*very high confidence*).

Research gaps remain on the impact that climate change will have on crop nutrition and yield in relation to specific crops and geographic regions (*very high confidence*). For food quality, information is lacking regarding global rice and maize, with only weak evidence existing for soybeans. Furthermore, global research on food quantity is mainly focused on wheat yields, but remains scarce for maize, rice, and soybean. In Southeast Asia however, rice is the most extensively studied crop, while in Africa, maize is the most extensively researched.

In the face of climate change, a major challenge will stem from meeting the nutritional requirements of global consumers, rather than solely caloric supply (*very high confidence*). A major focus on plant breeding efforts is aiming to address this concern.

Future opportunities for ensuring food security rely on innovation, direct mitigation and adaptation approaches (*very high confidence*). Specific measures include shifting the four main food crops of production to more climatically suitable crops and adoption of climate-smart agriculture by farmers.

1. Introduction, Framing & Context

The purpose of this report is to update the recent scientific findings since the latest IPCC assessment report, AR5 published in 2013-2014. This report focuses on the four main food crops globally, namely: wheat, maize, rice, and soybean. When possible, this report includes a geographic focus on Southeast Asia (SEA) and Africa, due to the disproportionately high levels of food insecurity in these areas (FAO Report, 2009). Despite the wide range of factors which contribute to food insecurity, this report focuses solely on 'food quality' (crop nutrition) and 'food quantity' (crop yield). The dialogue on food security globally is diverse and broad. Many consumers globally lack diets which meet nutritional requirements. In parallel, massive populations are still working towards basic caloric access. A systematic literature review was therefore conducted on recent scientific peer-reviewed research covering food quality and food quantity during the period of 2013 to 2019. The report begins by framing previous research regarding food quality and food quantity, namely the IPCC AR5 and the SR1.5, then continues to present the main drivers for food security (Figure 1) as well as the latest research. Finally, the report concludes by presenting research gaps and future opportunities for addressing food security in the context of climate change.

In the systematic review process, 490 papers were initially identified using Scopus by searching for research papers including the following keywords for food quantity: food security, crop yield, climate change, and then each specific crop type (maize, wheat, rice, and corn), and the following keywords for food quality: food security, food quality, climate change, and nutrition. Both searches were filtered for papers published between 2013-2019. Through an abstract and title screening, the 490 research papers were filtered for relevancy which resulted in 178 papers being selected for further research, each reviewed by two authors. The results have been divided into three main focus areas: impacts on food quality (12.92%), impacts on food quantity (51.12%), and future opportunities to adapt to climate change (35.96%). We ended the report with 86 peer-reviewed scientific articles.

1. 1. Summary of AR5, Chapter 7 & Summary of SRCCL, Chapter 5

According to the recent IPCC findings, (Porter et al., 2015; IPCC, 2019) there is high confidence that all aspects of food security are being affected by climate change. Concerning the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change will have a negative impact on food production. This is particularly the case for local temperature increases of 2°C or more. However, there is a medium confidence that some individual locations may benefit. This leads to the conclusion that with the magnitude and the frequency of extreme weather events, food production will be reduced and therefore affect the security of the entire food system. This will further decrease the stability of food supply while, at the same time, the increased levels of CO_2 in the atmosphere may lower the nutritional quality of crops. These findings are showing high confidence and although the higher levels of CO_2 are expected to benefit crop productivity at minor temperature increases, there is high confidence reached among the scientific community that this would diminish nutritional food quality.

Evidence shows that climate change will affect food quality through both biotic and abiotic stresses (Ceccarelli, Cerulo, Canfora, & Di Penta, 2010). These changes may influence crop quality by altering carbon and nutrient uptake and biochemical processes, mainly those associated with secondary compounds and others which redistribute and store compounds during crop development and maturation.

Overall, the evidence shows (IPCC, 2019) that not only is the relationship between weather and yields often crop and region specific, but also quality specific. With this in mind, and in order to provide more information on the impacts and correlations between climate change and the quality and the quantity of main crops globally, and in Africa and Southeast Asia, this report provides the systematic literature review of the most recent research.

Definition of "Food Security", "Food Quality" and "Food Quantity"

- According to the IPCC Special Report on Climate Change and Land (2019), **food security** is referred as a condition when all people have access to healthy and sufficient food to satisfy their daily dietary needs.
- Crop, or **food quality**, refers to phytonutrient and secondary metabolite profiles and associated health and sensory properties that influence consumer buying decisions (Ahmed and Stepp, 2016).
- In this paper, **food quantity** is defined as the total amount of crop yield of each staple food commodity.

Identified Climate Drivers of Food Security

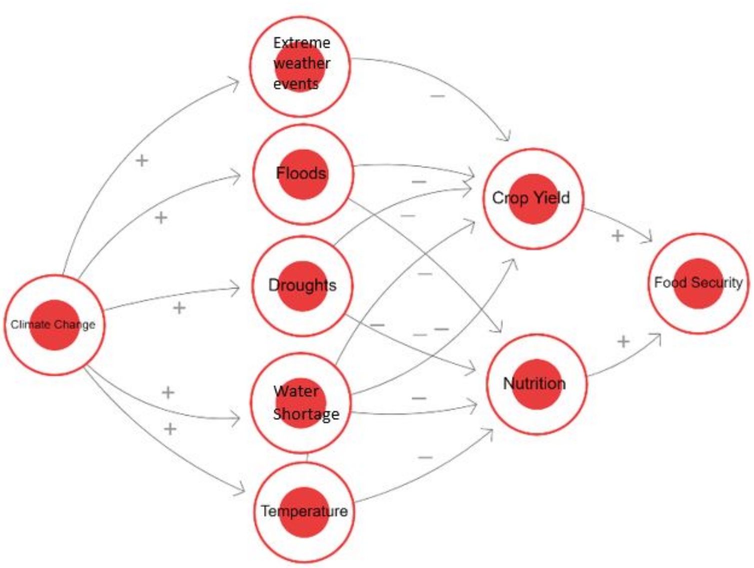


Figure 1. Own illustration. Climate change leads to increased risk of extreme weather event (Lesk et al., 2016, Gaupp et al., 2019, Liu et al., 2019), flooding (Lesk, Rohwani, Ramankuntty, 2016), changes in precipitation patterns (Adhikari et al., 2015; Omoyo, Wakhungu & Oteng'i, 2015; Mkonda & He, 2017; Trisurat, Aekakkararungroj, Ma & Johnston, 2018; Tesfaye et al., 2018; Seyoum et al., 2017), droughts (Wang et al., 2018; Trisurat, Aekakkararungroj, Ma & Johnston, 2018; Tesfaye et al., 2018), as well as increased temperatures (Dier et al., 2019; Asseng et al., 2019; McGranahan & Poling, 2018). All of these factors have been found to negatively impact crop yield and nutrition (Shrestha, Thin & Deb, 2014; Adhikari et al., 2015; Omoyo, Wakhungu & Oteng'i, 2015; Mkonda & He, 2017; Seyoum et al., 2017).

2. Impacts on Food Quality

Food quality has been seen as a critical factor under the influence of climate change. This is due to the reliance on food quality for protein and mineral nutrition, key implications for meeting the growing needs of human food security. Most research on food quality has been conducted on a global scale, however, Africa has a few notable research studies concerning the protein and mineral quality of maize production under climate change. When discussing crop nutritional quality, macro nutrients refer to nitrogen, phosphorous, and potassium, whereas micronutrients refer to zinc and iron concentrations. Macro and micro define the relative amounts of the specific nutrient as typically found in the crop (White & Brown, 2010).

Predicting the effects of climate change on food nutrition is challenging due to the complex relationship between various interacting environmental factors which are in constant shift (Köhler, Huber, Bernacchi, & Baxter, 2019). A few factors include: crop type, intensity or duration of stress, genotype or crop genetics, and developmental stage or growth stage of the crop (Soares, Santos, Carvalho, & Pintado, 2019). Both positive and negative interactions can be found between the climatic factors and both macro and micro nutrients available in the soil, and hence available for plant uptake and human consumption (Soares et al., 2019).

Globally, research studies are aimed to analyze the impacts of elevated CO_2 (eCO_2), elevated temperature (eTemp), and predicted climate (PC), or 700 μmol mol^{-1} CO_2 and 3 °C temperature rise. Amongst these three impacts, eCO_2 is considered the main factor in determining changes of accumulation of minerals and protein in crop plants under climate change (Soares et al., 2019).

2. 1. Global

2.1.1. Wheat

To begin with global wheat production, the main conclusions for wheat quality impacts on an aggregate scale include: redistribution of nitrogen throughout the plant, increased speed through which the growth stages progress, a varied impact on protein concentration, and N (nitrogen) limitation as the core offset to counterbalance the eCO_2 stimulus effect. Any benefits to grain and protein yield are likely to be cancelled by rising temperatures and rainfall shifts, but this result varies between regions (Asseng et al., 2019). Under PC (predicted climate) conditions, the growth rate was increased and the straw and grain yield was reduced. Additionally, the spike number per wheat plant declined, particularly in plants which were given sufficient nitrogen (Asif et al., 2019). PC illustrated no effect on grain protein concentration, but did reduce total mass of protein in whole grains of single plant (Asif et al., 2019). Under eCO_2 conditions, the location and timing of nitrogen uptake was altered for both main periods: (1) remobilization of vegetative nitrogen taken up before anthesis, or flowering and (2) post-anthesis, or after flowering, nitrogen uptake (Dier et al., 2019). A growth stimulus effect from eCO_2 can be identified, however, this stimulus is limited due to available nitrogen (Asseng et al., 2019). More specifically, eCO_2 increased grain N yield (8-12%), NUE or nitrogen use efficiency (13-18%), and N uptake efficiency (10-12%). Grain N concentration decreased in both years (-1 to -6%) and was more strongly affected by eCO_2 than by average N content per grain (Dier et al., 2019).

Under eTemp conditions, or elevated temperatures expected from climate change, the wheat growth period was increased with a decreased grain yield. For mineral and protein quality, reduced grain quality was identified, more specifically, an increase in fiber and a decrease in wet gluten, protein, total soluble sugars, and starch (Tian et al,. 2019). It is important to note that certain adaptations which benefit grain yield, do not always benefit grain quality. New genotypes for warm temperature wheat could boost global yields 7% and protein yield by 2%, but with a reduced grain protein concentrations, a relative change of -8.6% (Asseng et al., 2019). As a direct climatic effect, low-rainfall regions are expected to experience lower or more variable grain and protein yields (Asseng et al., 2019).

2.1.2. Soybean

Globally, soybean quality was analyzed for Fe and Zn deficiencies. Research found that (1) eCO_2 decreased Fe in soybean seeds in both seasons (−8.7 and −7.7%) and Zn concentration in one season (−8.9%), and (2) elevated temperatures (eTemp) found the opposite effect. Additionally, studies with both eTemp and eCO_2 generally restored seed Fe and Zn levels (Köhler et al., 2019).

2.2. Africa

One impact of climate change is the increase of severe droughts, especially in existing arid regions globally. Two areas in focus within Africa are Kapchorwa, Uganda and Teso South, Kenya, which experienced drought during the second season in 2016. Severe drought in East Africa is expected to decrease both nutrient concentration and total nutrients, both macro and micro, accumulated in maize. During milder droughts, research found that micronutrient concentration of edible maize increased, however, this effect is paired with a decreased yield (Fischer, Hilger, Piepho, Jordan, & Cadish, 2019). Particularly the strong drought effect on micronutrient contents is seen as a concern since human micronutrient deficiencies, for example Fe and Zn, represent some of the most common deficiencies found in East Africa (Fischer et al., 2019). This reinforces the escalated and uneven impact of changes to food quality due to climate change. Bioavailability of crop nutrients for human consumption is tied to nutrient mobility within the plant and soil systems, which is reliant upon nutrient transport through available water and hence are drought susceptible (Fischer et al., 2019).

3. Impacts on Food Quantity/Yields

Climate change is expected to result in global yield declines for the main crops globally, namely, maize, wheat, and soy. The counterfactual analysis, used by Iizumi et al. (2018) found that due to climate change in the past three decades the global mean of yields were reduced by 4.1% (maize), 1.8% (wheat) and 4.5% (soybeans), on a global scale. However, despite global declines in total crop yields, studies consistently find that climate change will affect geographic regions differently. Negative impacts on food quantity tend to be experienced by countries in lower latitudes while some high latitude countries can expect increases in the yield of certain crops. The tropics are typically considered to be the regions that will suffer most in the long term by climate change (see Appendix 1).

Despite increasing efforts in recent years to understand the impact that climate change will have on crop yield and food security, quantifying the relationship between climate change and global crop yield trends remains a challenge. This has to do in part with the fact that crop yield is influenced by many external factors which makes identifying climate related impacts especially challenging at aggregate level.

3. 1. Global

A study which assessed global cereal production found that droughts and extreme heat are playing an increasingly significant role in reducing global cereal production (Lesk, Rowhani, & Ramankutty, 2016). While most studies found that patterns in crop yield vary per region, there is a general consensus that crop production in low latitudes will experience the most negative effects of climate change (Lesk et al., 2016; Challinor et al., 2014; Wang, Lai, Wang, Chen, & Lian, 2018; Iizumi et al., 2014).

While aiming to understand the impact of temperature increase on crop yield, one study found that each degree of warming experienced will result in average yield decreases of 6.0% for wheat, 3.2% for rice, 7.4% for maize, and 3.1% for soybean (Zhao et al., 2017). Similar findings were reported in research which focused on specific crop types. When analyzing climate impact on tons of production in recent years, rice and wheat yields were found to have decreased by 1.6 million tons, 5 million tons respectively, while maize yields were found to have experienced a marginal increase of 0.2 million tons annually in recent years (Ray et al., 2019). The same study found that recent climate change generally decreased yields across Europe, Sub-Saharan Africa and Australia, increased yields in Latin America, and had mixed responses in North and Central America and in Asia (Ray et al., 2019).

Despite expected positive impacts in some regions, particularly higher latitude regions, studies found that without adaptation, all regions producing wheat, rice and maize can expect production losses (Challinor et al., 2014). Research found a strong correlation between crop yield variability and two major atmospheric variabilities (e.g. El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Najafi, Pal, & Khanbilvardi, 2019). These findings outlined how climate variability will affect production of maize (EU and North America), rice (South America, Oceania and East Asia), sorghum (West Asia, Southeast Asia, North America, and Carribean), and soybean (North and South America, Oceania and South Asia) due to ENSO and NAO atmospheric patterns affecting weather and therefore crop yields (Najafi et al., 2019).

When analyzing global wheat, maize, and soybean production, Gaupp, Hall, Mitchell, & Dadson (2019) found that wheat faced the highest risk of regional breadbasket failure with both a 1.5°C and 2°C warming at 40% followed by maize at 35%, and soybean at 23%. A major driver of breadbasket failure or yield decline is drought frequency, severity, and duration which are expected to increase significantly for the Global Grain Production Area (GGPA) with climate change (Wang et al., 2018). Despite regional variations, the entire GGPA is prone to increased drought (Wang et al., 2018). Drought severity and its impact on yield is non-linear; research found that drought severity plays a more significant role in yield decline when shifting from moderate to severe as opposed to from extreme to exceptional (Leng & Hall, 2019). Research found that Canada and the USA are especially vulnerable to potential wheat production declines due to drought while, maize and rice yields are expected to be most impacted due to drought in India, Vietnam and Thailand (Leng & Hall, 2019).

3.1.1. Wheat

Balkovič J. et al (2014) illustrates that wheat production yields are vulnerable to several factors linked to climate change. Globally, temperature changes are playing a significant role in changing wheat yields. Studies also found that global wheat yields can be expected to decline by 4.1% to 6.4% with a temperature increase of 1°C (Liu et al., 2016; Zhao et al., 2017). One study, which aimed to quantify this yield loss in terms of weight, found that wheat yields could decline by 4–5 million tonnes for the same 1°C rise in mean temperature experienced during the growing period (Sendhil et al., 2016).

Elevated levels of atmospheric CO_2 are expected to have potential benefits for wheat and protein yield (Asseng et al., 2019). The impact of increased atmospheric CO_2 emissions was found to be strongest from 450 to 575 ppm, afterwhich only marginal differences were noted (McGranahan & Poling, 2018). When analyzing multiple factors however, studies found that any potential benefits from elevated atmospheric CO_2 concentrations will be counteracted by other impacts such as temperature increases as mentioned above as well as changes in precipitation patterns (Asseng et al., 2019). Additionally, several studies found that not all regions will be impacted equally (Challinor et al., 2014; Liu et al., 2019; Najafi et al., 2019; Iizumi et al., 2014). One study found that "hot growing" locations can expect increased frequency of extremely low yields and inter-annual variability (Liu et al., 2019). The implications of these findings are significant with regard to food security as India, which accounts for more than 14% of global wheat production, is amongst these hot growing locations (Liu et al., 2019). Finally, research suggests that the second half of the century will experience more significant yield losses than the first (Challinor et al., 2014).

3.2. Africa

Climate change has negatively impacted crop yields in Africa. However, there are regional differences observed regarding the four main crops covered in this systematic reading review. Among them, the most vulnerable crop in Africa is wheat. It is expected that close to 72% of wheat yields may decline in future while the decrease in other main crops (maize, rice and soybean) is expected to fall up to 45% during the 21 century (Adhikari, Nejadhasemi, &Woznicki, 2015). The effects of this trend have already impacted food security by an estimated 30% decrease (Mkonda, & He, 2017). Despite the expectation that future technological advancements will result in yield increases, research has found that this effect will be largely nullified by warmer and drier climatic conditions (Hoffman, Kemanian, & Forest, 2018).

Despite wheat being the most vulnerable to Africa, maize is the crop most studied among the research compiled related to this region. In the medium to long-term future, increased warming is projected to lead to lower yields (Stevens & Madani, 2016). Among the main manifestations of the climate impacts, drought patterns play a significant role. Between the four main manifestations identified by Seyoum, Chauhan, Rachaputri, Fekybelu, & Prasanna (2017), it is the early terminal drought, compared with low-stress drought pattern, that results in up to an 80% yield reduction. These, together with other findings (Munishi, Lema, & Ndakidemi, 2015), show a strong linkage between severe climate change induced droughts and declining annual maize yields. The results from the CERES-Maize model simulation applied to the commonly grown maize types in Eastern and Southern Africa revealed that an increasingly warmer and drier climate will lead to higher average simulated maize yield reduction of 21% and 33%, respectively for each region (Amazou et al., 2019). Additionally, warming alone is predicted to lead to 11% and 21% losses, respectively (Tesfaye et al., 2018).

Without adapting fertilizing practices, a 2.0 °C temperature increase is expected to result in higher yield loses than a 1.5 °C temperature increase (Faye et al., 2018). More specifically, under RCP 4.5 and RCP 8.5 scenarios, and considering the current farming practices, the decrease in maize yield is predicted to be 57% and 51% respectively (Traore et al., 2017). Other future projections indicate that maize yield decreases on average by 20 % in 2050s relative to the baseline (1980–2009) due to climate change. Still, although the negative impact on yield is very likely, the extent of impact remains uncertain (Kassie et al., 2015).

When compared regionally, Southern, East and West Africa experienced different yield impacts due to climate change. In the case of Southern Africa, the overall projections indicate an average of 18% maize yield losses in the near future, while this decline is expected to reach 30% during the second part of this century (Zinyengere, Crespo, & Hachigonta, 2013). When analyzing yield losses for three regions in South Africa using Modified Modelling Solution (MMS) simulation, grain yields showed reductions of 27.6% (Bloemfontein), 24.3% (Lichtenburg) and 18.7% (Nelspruit) (Mangani, Tesfamarian, Bellocchi & Hassen, 2018). In the western parts of Africa, the impact of warm and dry conditions are manifested uniformly and lead to potential crop yield losses across the region. Similarly, a correlation between yield variability and yield declines has been observed (Parkes, Sultan, & Clais, 2018). In East Africa, increasing temperatures have led to a 0.07 tons/ha/decade yield decrease at the 95% confidence level, accompanied by high inter-annual variation (Mumo, Yu & Fang, 2018). Here, close to 70% of yield variance was linked to varying seasonal climate indices (Mumo, Yu & Fang, 2018). When considering RCP scenarios, maize yields are expected to decrease by 3.1% under RCP 4.5 and 5.3% under RCP 8.5 (Luhunga, 2017).

While acknowledging the increase in rice production over the last few decades in parts of sub-Saharan Africa, Nhamo, Rodenburg, Zenna, Makombe & Luzi-Kihupi (2014) find that the relative yield gains have decreased. The particular causes for such results are associated with weed management, organic fertilizer application, mineral fertilizer application and tied ridges (Nhamo et al., 2014).

As for the wheat, the climate sensitivity analyses show that the increase between 1 °C and 4 °C would lead to 17.6% wheat yield losses. Additionally, the reduction of the agricultural land due to sea level rise, particularly in the North Nile Delta will have further negative impacts on wheat yield crop quantity in Africa (Kheir et al., 2019).

3.3. Southeast Asia

In Southeast Asia, rice is the most consumed staple food, in comparison with maize and soybean, the other staple foods produced in this region (Birthal, Joshi, Roy, & Pandey, 2019). Rice is grown in many parts of Southeast Asia including Indonesia, Thailand, Vietnam, Myanmar, Philippines, Cambodia, Laos and Malaysia. Unlike rice, wheat is imported from outside the region (Timmer, 2015). Given the near non-existence of wheat production in Southeast Asia, there is a natural lack of research on wheat production in this region.

Rice farming takes on two common practices in Southeast Asia, namely, irrigated paddy and rainfed rice (Shrestha, Thin, & Deb, 2014). Both types have been found to be vulnerable to the effects of climate change (Shrestha et al., 2014). An often-cited study by Welch et al. (2010) estimated that climate change will cause up to a 10% reduction in rice yield in the main producing countries in South and Southeast Asia (Welch et al., 2010, as cited in Lyman, Jagadish, Nalley, Dixon, & Siebenmorgen, 2013). One study found that an increase of 1°C during the growing season can lead to a 9% -13.8% reduction of total head rice yield which usually determines the milled rice quality (Lyman et al., 2013).

According to the systematic literature review process, climate change factors (i.e. rising temperatures, changing rainfall patterns, and sea-level rise) have affected and will continue to impact staple food production in Southeast Asia. Few areas are projected to benefit from climate change and will have an increased rice yield, albeit the majority will face yield reductions. Among them, Thailand is exposed to the largest reduction in rice yields (Trisurat et al., 2018). Yet, a study using the Environmental Policy Integrated Climate (EPIC) model found mixed results of rice yields in Northeast Thailand. Under RCP 8.5 this region will have an average increase of 0.7% by 2060-2079 followed by decline by 8.4% by 2080-2099 in all types of management. However, a higher increase; 2.6% under RCP 8.5 to about 22.7% is expected under RCP 6.0 by 2080-2099 in rainfed rice crops (Arunrat, Pumijumnong, & Hatano, 2017).

Laos and Cambodia are vulnerable to drought due to the topography and soil type. Trisurat et al. (2018) found that these countries will not be able to suffice their domestic rice needs by 2030. In Cambodia, extreme drought will result in a reduction of 4.2% in irrigated paddy crop yields, and 4% in rainfed rice crop yields relative to baseline. Meanwhile, during monsoon season, the annual runoff will increase by 6-26% (Trisurat et al., 2018) may result in soil nutrition loss. According to the results of three crop models (HadGEM3, YSU-RSM and RegCM4), the average rice yield decrease is expected to reach 16.2% under RCP 4.5 from 2021 to 2030, which will lead to a 10.57% reduction of Cambodia's Gross Domestic Product (GDP) (Kim, Park, Chun, & Li, 2018).

Under A2 scenario (comparable with RCP 8.5 according to IPCC AR5), Vietnam will lose one-third of the total rice yield in 2020-2029, about 16% in the 2030s and about 21% in 2040-2050 (Jiang et al., 2019). A greater loss occurs during summer, almost half of the total rice yield within this season will be reduced due to climate change, and about one-third will get lost during winter (Jiang et al., 2019). Other than seasonal variability, seawater intrusion due to sea-level rise will impact yields as well. A study in the province of Thua Thie Hue found that saline conditions will significantly cause a lower yield (Dam, Amjath-Babu, Bellingrath-Kimura & Zander, 2019).

While there is a lack of findings related to the production of the four staple crops in the Philippines, there were studies which identified and discussed rice yields for Myanmar, Malaysia and Indonesia. A study on Myanmar found that in regions where precipitation is expected to increase water management will become increasingly challenging due to decreasing irrigation water requirements in irrigated paddies and increasing potential yield of rainfed rice (Shrestha et al., 2014). Therefore, without mitigation efforts, increasing precipitation will lead to floods and could also lead to crop failure. In Malaysia, 'it is expected that by 2050 the 2.0ºC surface temperature increase will account for 13%-80% of rice yield loss.' (Siwar, Ahmed, & Begum, 2013), and another study found a reduction of 31.35% until 2030 (Vaghefi, Shamsudin, Radam, & Rahim, 2016). While in Indonesia, El Niño Southern Oscillation (ENSO) has negatively impacted the production of rice (both irrigated and non-irrigated), soybean and maize (Ruminta & Handoko, 2016).

4. Research Gaps & Future Opportunities

The updated research findings explained in Chapter 2 and Chapter 3 have provided evidence on the impacts of climate change on food security in terms of food quality and food quantity. Overall, food security has been extensively researched after the IPCC AR5 was published in 2013-2014. However, there is a lack of information and evidence on several crops in different scales and regions. This section will discuss briefly the research gaps in food quality and food quantity studies, and further, will explain the future opportunities when facing the stress of climate change on food security.

4.1. Research Gaps

Research gaps in food quality and food quantity are generally found in different staple foods. In terms of food quality, there exist significant gaps in the research since 2013 regarding the influence of climate change on crop nutrition in specific geographical regions globally. Furthermore, global rice and global maize food quality, protein and mineral concentrations, are missing, with only weak evidence existing for soybeans.

In the context of food quantity, wheat is the most well-researched staple food among four staple food commodities globally. Limited evidence was found for maize, rice and soybean. Many studies cover information on climate change impacts on maize in Africa. However, the study on yield quantity of rice, wheat and soy, is scarce. In Southeast Asia, rice is the most extensively studied among other crops. Research on maize and soy is limited and no reference was found specifically about wheat.

4.2. Future Opportunities

More than one-third of the total of selected papers from the systematic review process discusses adaptation and mitigation efforts in addressing food quality and food quantity issues due to climate change. Future opportunities for food security (Figure 2) can be classified into four main categories, including shifting to new main crops, new protein sources, climate modelling and mitigation and adaptation in agricultural practices.

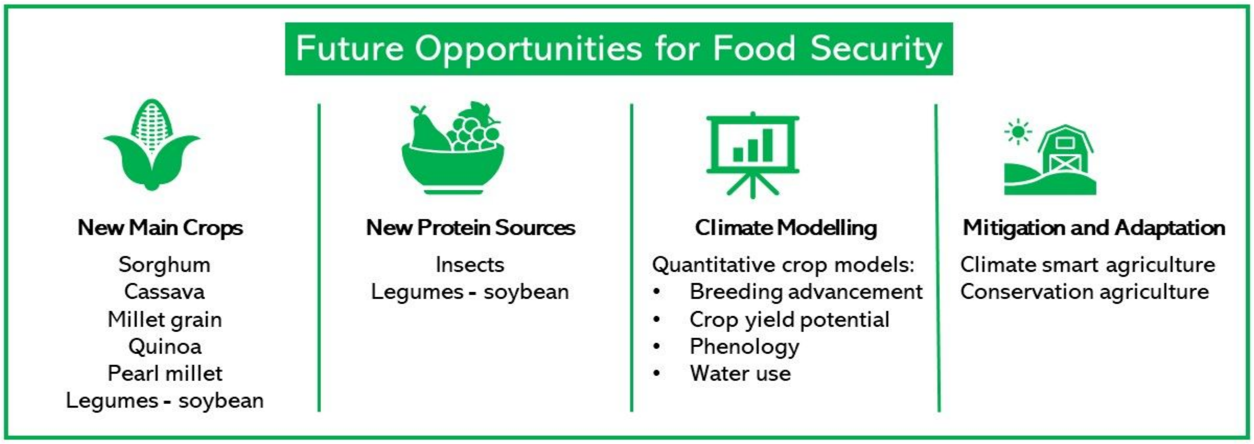


Figure 2. Own Illustration. (a) New main crops: sorghum (Kumar et al., 2015), cassava (Brown, Cavagnaro, Gleadow, & Miller, 2016), millet grain (Saleh, Zhang, Chen, & Shen, 2013), quinoa (Bazile et al., 2016), pearl millet (Kumar, Romer, Kaur, Kumar, & Gupta, 2018; Jukanti, Gowda, Rai, Manga, & Bhatt., 2016), legumes-soybean (Rios-Castillo, Acosta, Samudio-Núñez, Hruska, & Gregolin, 2018), (b) New protein sources: Insects (Yates-Doerr E., 2015), Legumes/Soybeans (Van Mierlo, Rohmer, & Gerdessen, 2017) (c) Climate Modelling: breeding advancement (Gbegbelegbe et al., 2017), crop yield potential, phenology and water quantity (Rötter, Tao, Höhn , & Palosuo, 2015.) (d) Mitigation and Adaptation: climate-smart agriculture (Hammed, Olonruntoba, & Ana, 2019, Seleiman & Kheir, 2018) and conservation agriculture (Lal, 2016).

In 2050, the greatest challenge to food security will be fulfilling the nutritional requirements of global consumers, rather than solely providing adequate calories.

Research priorities for plant breeding should emphasize nutritional crop quality for human dietary health and the ability of crops to maintain yields amongst changing climatic conditions (Nelson et al., 2018; Halford, Curtis, Chen, & Huang, 2015; Fischer et al., 2019; Ekpa, Palacios-Rojas, Kruseman, Fogliano, Linnemann, 2018; Choundhary et al., 2019; Reynolds et al., 2016)**.** Many plants with higher water or nitrogen use efficiency, ability to withstand colder temperatures, salinity or water submergence are being developed, in addition to enriching staple crops with essential vitamins or metals, also known as biofortification (Ricroch, & Hénard-Damave, 2016). The cheapest source of micronutrients is sorghum, which is also a valid crop for biofortification (Kumar et al., 2015). More specific examples include breeding rice cultivars which combine both drought and heat stress tolerance with a focus on nutritional values both in Africa (Mukamuhirwa et al., 2019), as well as globally (Bahuguna et al., 2018; Kingra, Kaur, Kaur, 2019). Capturing the full diversity of edible plant genomes existing globally can assist with breeding crops able to withstand changing climatic conditions. With over 50,000 known edible plants globally, only three crops, maize (Zea mays), wheat (Triticum aestivum) and rice (Oryza sativa) provide two-thirds of plant-derived food today (Cheng, Mayes, Dalle, Demissew, & Massawe, 2017).

As our climate undergoes changes from anthropogenic influences, in order to ensure food security into the future, one possibility is to shift the four main food crops of production (maize, wheat, soy, and rice) to other, more climatically suitable, crops. A few key examples include millet grain, quinoa, pearl millet, grain sorghum, and cassava. Several of these 'new' crops are being grown in specific regions worldwide, for example quinoa in the Andean region (Bazile et al., 2016) or millet grain in the semiarid tropics of Africa and Asia (Saleh et al., 2013); however, many researchers are looking as to the geographic potential of expansion into other production systems for food security. Furthermore, several studies emphasize the needs to shift in protein sources. However, there is a problem with social acceptability of new protein sources, such as insects (Yates-Doerr, 2015).

Research also focuses on the technological approach in analysing digital information; crop modelling has become one of the most suggested approaches. Crop modeling is a critical tool used to evaluate the potential consequences of climate change on crop production under various scenarios into the future, as well as developing ideotypes, or model plants, for various cultivation environments (Rötter, Tao, Höhn, & Palosuo, 2015). This field of research has exciting novel developments including cultivar-specific and region-specific parameters to remove previous model assumptions (Gbegbelegbe et al., 2017).

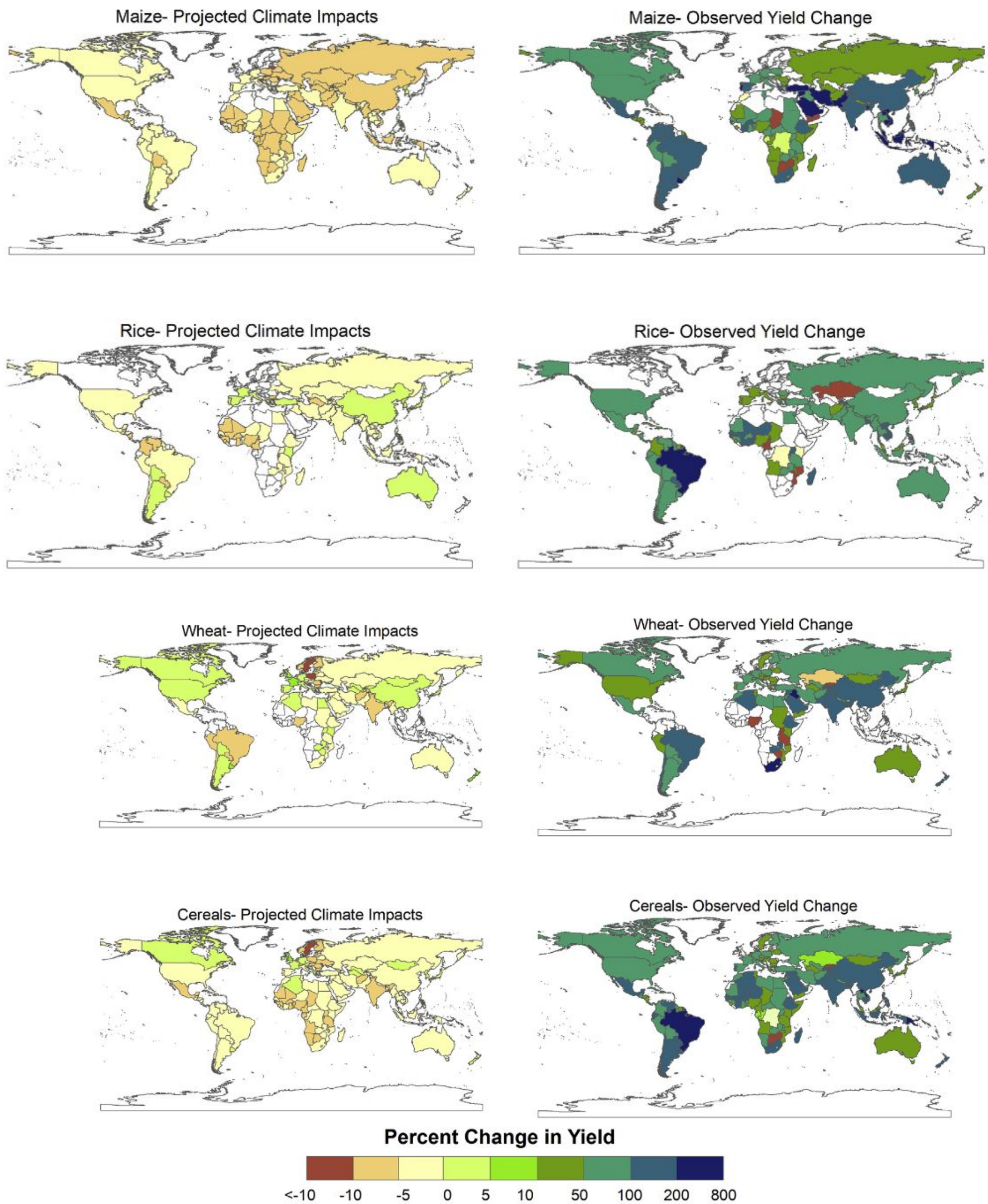
Although there are various innovations and new findings are useful for future prospects in addressing food security in a changing climate, direct approaches in adaptation and mitigation are highly relevant in the short-term and long-term. Two common typologies of adaptation and mitigation on-farm include climate-smart agriculture and conservation agriculture. Globally, Integrated Pest Management (IPM) has been shown to decrease chemical application and hence GHG emissions, while maintaining crop yields (Muniappan, & Heinrichs, 2015). Regionally, research has been conducted in Southeast Asia on the application of agroforestry in Vietnam (Nguyen, Hoang, Öbornd, & van Noordwijk , 2013) and on conservation agriculture in the Central Dry Zone of Myanmar (Herridge et al., 2019). In Africa, the use of organic fertilizers, also critical for soil carbon sequestration, is found to increase yields for maize and soybean production in both dry and rainy climatic seasons (Hammed et al., 2019). Similarly, despite increasing climate pressures on yields, farmers in certain sub-Saharan African countries have managed to avoid extreme yield declines due to innovation in weed management, organic fertilizer application, mineral fertilizer application and tied ridges (Nhamo et al., 2014). Physical soil management is also important to a conservation agricultural approach, as conservation tillage has shown in Africa to increase maize yields by 78% on average when compared to conventional practices (Mubiru et al., 2017). In an earlier African study for maize, legume intercropping with maize yield has proven to increase maize yields even under pronounced climate stress conditions (Arslan et al., 2015).

Contributions

The Executive Summary was drafted by Boris Matijas and Chapter 1 was drafted by Avital Meira van Meijeren Karp. Chapter 2 was written by Anna Gomes, with Chapter 3 being written by Adelina Chandra, Boris Matijas, and Avital Meira van Meijeren Karp. Chapter 4 was written by Adelina Chandra and Anna Gomes. The entire author team conducted a full review of the draft paper and worked to create the illustrations.

Appendix

Appendix 1 Global Crop Yield Change



Appendix 1. Crop yield change of rice, maize, wheat, and cereals in 2020s in comparison with observed yield change in 2016. Negative crop change will especially affect low-latitude countries (Aggarwal, Vyas, Thornton, Campbell, & Kropff, 2019).

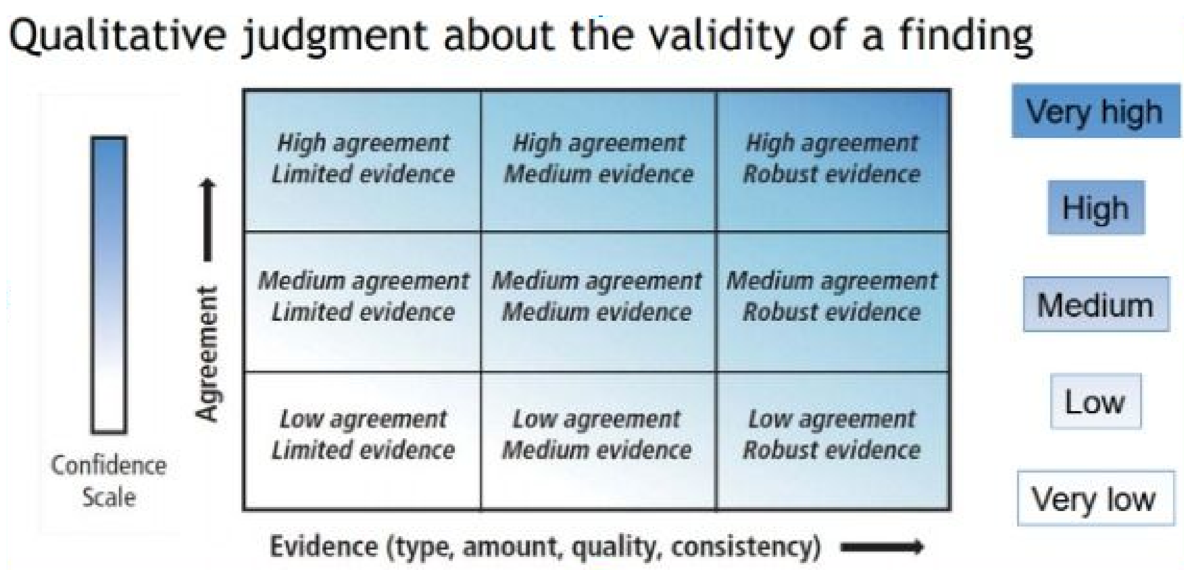
Appendix 2 Confidence Intervals

As an authoring team, we came to a consensus regarding assigning confidence intervals to our Executive Summary statements. For example, if a statement has four or more published peer-reviewed academic articles published since 2013 supporting the claim, the statement is considered high-evidence.

Agreement: Determined amongst the four main authors based on evidence and confidence levels.

Evidence: robust evidence (4+ references), medium evidence (3+ references), and limited evidence (1+ references).

Once the evidence and agreement level were determined, the confidence interval could be established and included in the Executive Summary. High confidence means that there is a high level of agreement and evidence, whereas low confidence denotes that the categorization of magnitude is based on few studies. For example, high agreement and robust evidence is 'very high' confidence. Or limited evidence and medium agreement as low confidence.



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