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Review

Mitigation of emerging implications of climate change on food production systems

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ABSTRACT

Crops, livestock and seafood are major contributors to global economy. Agriculture and fisheries are especially dependent on climate. Thus, elevated temperatures and carbon dioxide levels can have large impacts on appropriate nutrient levels, soil moisture, water availability and various other critical performance conditions. Changes in drought and flood frequency and severity can pose severe challenges to farmers and threaten food safety. In addition, increasingly warmer water temperatures are likely to shift the habitat ranges of many fish and shellfish species, ultimately disrupting ecosystems. In general, climate change will probably have negative implications for farming, animal husbandry and fishing. The effects of climate change must be taken into account as a key aspect along with other evolving factors with a potential impact on agricultural production, such as changes in agricultural practices and technology; all of them with a serious impact on food availability and price. This review is intended to provide critical and timely information on climate change and its implications in the food production/consumption system, paying special attention to the available mitigation strategies.

1. Introduction to the sensitivity of food to climate

Food production is highly sensitive to the weather, that is the main focus of this manuscript, together with the search for remediation strategies in all key areas, such as food production and quality yields, irrigation water requirements, crops and livestock technological changes, loss of arable lands by erosion, fish production needs, and all kind of emerging risks with effects on food security and nutrition quality. In this introduction, we will briefly summarize all these issues, which will be treated in depth in the following sections.

A year with an anomalous rainfall regime, sudden temperature changes, or extreme weather events, have harmful effects on performance in agricultural and livestock activities. Although modern technologies can alleviate these adverse effects on yields, we cannot forget the strong impact of recent droughts on world cereal production (FAO, 2011) and its great potential vulnerability. Machine learning (ML) algorithms have advanced triggering breakthroughs in aiding climate analysis (Schneider et al 2017; Reichstein et al., 2019). Artificial intelligence (AI) can then build on discovered climate connections to provide enhanced warnings of approaching weather features, including extreme events (Huntingford et al., 2019).

Climate change and global warming are already having comparable effects on the efficiency in food production as well as on its quality worldwide (Easterling et al., 2007; FAO, 2019b). These effects have been tempered by the increase in world food production achieved in recent decades. Unfortunately, differentiating the effects of global warming and climate change on the rest of the factors that affect the world agricultural and livestock production is not easy, but studies have shown that increases in corn and wheat production since 1980 would be a 5% higher in the absence of the effects of climate change. If the rest of the factors were invariant, the high levels of carbon dioxide (the main driver of global warming) would be possible to increase the production of rice, soy, wheat and other crops. We must bear in mind that the climate change will significantly affect the duration and quality of the growing season. Nor should we forget the damage to crops that will increase dramatically due to droughts, floods or forest fires that will become increasingly frequent and intense phenomena.

The latest IPCC report (IPCC, 2019) predicted modification in the areas suitable for food production, freshwater, as well as biodiversity. Human use affects more than 70% of the global, ice-free land surface. The yields of rain-fed agriculture would fall around 50% in all of Africa from 2020 with an average increase in temperature around 1–3 °C. It is difficult to predict food and feed production behaviour, especially on a local scale. For example, impacts on pollinators (Kehrberger &

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Holzschuh, 2019), such as bees, are already under great pressure from habitat loss and intensive agriculture. The same is about the effects of global warming on pests and diseases in crops (Zayan, 2019) or livestock (Kebede et al., 2018).

Fisheries provide proteins supply for at least one-half the world's population. Currently, there is already a significant stress due to overexploitation and the adverse effects of pollution in seas and inland waters. That is why this food source runs a special risk (FAO, 2018a,b). Warmer surface waters in oceans and inland waters, together with rising sea levels and ice melting, are expected to adverse effect upon many fish species. Although some marine species are already migrating to high latitudes; others, such as Arctic and freshwater species, have nowhere to go and are concerned with extinction. In addition, oceans are absorbing increasing amounts of CO_2 that yields acidifying effects with important impacts upon marine life.

In any case, the previous threats can affect food security and, more specifically, the availability at a reasonable price of food for a global population of 8 billion people (Hertel, 2016). A 2011 Foresight report (Government Office for Science, 2011) concluded that, in the short term, climate change is not an important factor in the equation as compared to the increase in global requirements of food expected for the next decade (United Nations, 2017). As the standard of living increases, the population tends to demand greater amounts of food (especially meat), what suggests a future of increasingly volatile food prices. The Human Development report (2019) concluded that international policy is key to redress the shock to livelihoods of rural people in poor countries, and the spikes in food prices by drops in global yields.

Finally, we must underline that food production is a substantial contributor to greenhouse gas emissions and a source of environmental degradation; hence, it can magnify and accelerate climate change. Farming contributes about 15% of global greenhouse gas emissions —roughly as much as transport. More pessimistic assessments claim that the overall contribution of food production to atmospheric emissions can reach 30%. Therefore, effectively restricting the long-terms effects will require making food production more resistant to the climate and the achievement of significantly lower carbon footprints. Countries and their citizens suffer unequally the threat of food supply. Some countries, which lose arable land and fisheries, lack the resources to maintain food security at a reasonable cost. Others are more vulnerable to unfavourable international trade agreements. Finally, regional conflicts disrupt food distribution.

2. Reduced yields

Crop and livestock productivity may diminish by elevated temperatures, drought-related stress or increased CO_2 concentrations. Their effects on crops and livestock may arise suddenly or gradually. These events can be faced before, during and after the disaster. *Risk*, *threat* and *vulnerability* are three inter-connected concepts . *Risk* is a combined measure of probability and degree of harm of a territory and its inhabitants being affected by natural hazards. It follows equation:

$$Risk = Threat \times Vulnerability \quad (1)$$

Threat is the probability of a natural hazard to occur to a certain extent, and with a certain intensity and duration. The human factor has no impact on threat. Finally, *vulnerability* is associated to the social impact of an adverse phenomenon and must thus, be properly managed in order to avoid or reduce the unwanted effects of natural events and their associated risks. For this reason, risk is usually assessed for prevention(to prevent hazards in order to alleviate, diminish or avoid their potential damage). Extreme climate events, such as droughts, floods, and too high or low temperatures, can have unwanted effects on crops including corn, soybean, wheat and small grains, rice, cotton, pasture, and fruits (Aryal et al., 2019).

Several strategies for crop and livestock have been devised to increase their resilience to extreme climate. Therefore, crops can be managed by breeding for drought and temperature tolerance, adjusting loads and irrigation, pruning canopies, using particle films and shading, and selecting appropriate cultivars (Sofi et al., 2019). In turn, livestock can be managed by selecting better breeds; improving nutrition during periods of high heat load; using sunshades, evaporative cooling or mechanical ventilation; using rotational grazing to minimize damage to range and pasture; optimizing forage stock management and reducing herd size during drought periods (Osei-Amponsah et al., 2019). Water can be managed by installing more efficient irrigation systems or increasing the efficiency of existing ones; storing water in ponds and tanks; rationalizing water use to avoid wastage; and facilitating livestock access to water (United States Government Accountability Office, 2019). In any case, the most effective way of reducing vulnerability and its associated risks is by improving access to information (*e.g.*, with early warning systems), fostering R&D activities, and developing risk management, regional outreach, extension and education programs for farmers.

2.1. Mitigation strategies

Heat stress causes vast economic losses in both crops and livestock. Alleviating its effects requires sustaining animal productivity in hot environments through physical alteration of the environment, nutritional measures and the development of breeds that are more tolerant to heat stress. These strategies can be used individually or in combination for better results (Collier et al., 2006).

Days that the temperature–humidity index (THI) exceeds comfortable levels are steadily increasing in the American and European continents. The growing number of heads of cattle that are raised, as well as the intensification of production, presents as one of its greatest challenges the problems presented by heat stress of animals, which has serious negative effects on the health and biological function of this cattle altering its reproductive performance. In addition, it can induce feelings of hunger and thirst among cows. This issue has raised increasing concern because milk production and composition are being used as indicators for reduced welfare (Hu et al., 2016).

In the C4 Rice Project, researchers were working together to apply innovative scientific approaches to the development of high yielding rice varieties for smallholder farmers. Phase III had an emphasis on integrated 'systems' and 'synthetic' approaches to plant biology. Phase III ran from 2015 to 2019 and was co-ordinated by Jane Langdale at the University of Oxford. Advances in Phase III were sufficient to secure funding for a fourth phase that aims to develop a prototype for C4 metabolism (Vlad et al., 2019).

3. Increased irrigation

The impact of irrigation on the environment is felt mainly in the quantities of available crop soil and water, and in their quality. The effects arise mainly from changes in hydrological conditions caused by irrigation schemes. A number of world regions currently rely heavily on rain-fed agriculture and require abundant irrigation, which has increased cultivation costs and raised conflicts over access to water. This situation has promoted unwanted environmental problems arising from quantity and quality changes in soil and water (Thiery et al., 2020; Sloat et al., 2020; Dai et al., 2020). A few studies have addressed the effects of global warming on agricultural water use including changes in net irrigation, water demand and water uptake by crops. This is especially important because agriculture is the greatest user of fresh water for irrigation and accounts for 70% of all water used globally each year (Woznicki et al., 2015).

Climate projections have been used to estimate water demand for future irrigation (Gondim et al., 2012; Bakken et al., 2016), which are estimated to increase between 40 and 250% depending on the crop at the end of this century. The increased requirements have been ascribed to reduce water availability in the growing seasons, evapotranspiration and changes in crop phenology (Woznicki et al., 2015; Sloat et al., 2020; Dai et al., 2020). This causes great uncertainty about the predictions in the literature (Chung and Nkomozepi, 2012).

3.1. Particular cases and approaches

In a recent study, Kukal & Irmak (2018) investigated global warming effects on yield variability in maize, sorghum and soybean between 1968 and 2013 in the USA. The temperature trend in the studied period had a beneficial effect on maize but an adverse impact on sorghum and soybean. On the contrary, the precipitation trend had a positive effect on the three crops. Precipitation rise had significant positive sensitivity for almost all counties under non-irrigated conditions, meaning that all rain fed crop yields are benefitted by any increase in precipitation. For irrigated crops, relatively lesser proportion of counties show positive sensitivity, and with lower magnitudes than non-irrigated conditions, with increase in precipitation. Irrigated land exhibited considerably increased robustness, and even more effective mitigation of the climate impacts.

Cao et al. (2018) examined the effects of water stress on crop production over the 1996–2015 period, in various regions of China. They suggest that using the water footprint to assess the suitability of irrigation in order to implement water resources management policies, irrigation and the most effective crop variety worldwide. This would be the best way to achieve a viable adaptation of crops to environmental changes.

The advent of powerful computational resources has facilitated the monitoring and implementation of more effective solutions for the increased irrigation demand. The effects of irrigation on the water table and on soil salinity, drainage and groundwater, and those of mitigation strategies, can currently be simulated and predicted by using agro-hydro-salinity models such as SaltMod (SaltMod, 2001). Such models have allowed the effects of climatic conditions on agriculture to be predicted before they occur (Elliott et al., 2014; Ashour & Al-Najar, 2012). For example, Sun et al. (2019) identified, for areas of northern China, the best practices of water management and fertilization with N for summer cucumber in the greenhouse. They calibrated and validated models constructed from experimental data (applied to 240 scenarios with different water uses and various fertilization conditions) using environmental and economic indices to determine the best management practices.

Mahmoud & Gan (2019) used remote sensing and a geographical information system (GIS) to conduct a spatial and temporal study over the 1950–2013 period in Saudi Arabia. For this purpose, they collected information about evapotranspiration and modelled crop coefficients as a function of a 16-day time-series Moderate Resolution Imaging Spectro-radiometer normalized difference vegetation index. They used the information thus obtained to simulate daily evapotranspiration with the model of soil water balance and aggregated it to the monthly and annual evapotranspiration figures.

Riediger et al. (2014) examined the need for re-adaptation of agricultural irrigation in sandy soils from Ülzen County (Central Europe) by using computational modelling methods. By combining information on climate changes with soil- and crop-specific evapotranspiration models, they predicted the potential amounts of irrigation water needed to prevent crop failures up to the year 2070. In a scenario of increasing temperatures, the amount of groundwater available for agricultural practices in the future will be inadequate. Hence the importance of computational methods with a view to estimating irrigation requirements under the changing climate conditions.

The increased irrigation demand is also expected to affect infrastructure requirements. Zhang and Lin (2015) examined the effects of climate and irrigation infrastructure on irrigation water use and assessed the potential adaptive effects of more efficient irrigation infrastructure on water uses under current and future drought conditions by using models based on irrigation depth for the period 1985–2005 in USA western regions. They examined differences in infrastructure requirements associated to irrigation type (*e.g.*, rice and surface irrigation) and geographical constraints potentially affecting the selected irrigation infrastructure (*e.g.*, surface irrigation is unsuitable for undulating slopes). By using predictive models, they concluded that substantially reducing the surface-irrigated area in western USA —by at least 40%— would be the only way of keeping the irrigation depth at baseline climate. Hence, additional solute ions will be required to supplement changes in irrigation infrastructure and sustain USA agriculture at its present levels without even considering the increased food needs projected for the growing global population.

3.2. Mitigation strategies

The main challenge in mitigating a problem is anticipating it. As far as mitigating the impact of climate change is concerned, and based on Eq. (1), this amounts to decreasing vulnerability. Developing robust computational modelling programs can provide powerful tools for acting and decreasing risks before unwanted events occur. Installing sensors in critical (or vulnerable) regions to record climate events can be useful to construct models for specific regions. For example, prediction models for the Canadian state of Alberta (Alberta Agriculture and Rural Development, 2014) have allowed five key strategies to be developed for the future of the irrigation industry. The strategies focus on specific needs regarding *productivity*; *efficiency* (; *conservation*, *water supply*; and *environmental care*.

One especially worthy initiative in this context is PROHIMET, a thematic network created and originally supported by the CYTED Program (www.prohimet.org). PROHIMET is concerned with the problems posed by floods and droughts, and with their effects on climate change. Preliminary diagnoses have provided recommendations for appropriate implementation of early warning systems for drought and flooding. The first step to be taken in this direction is capacitation in vulnerable regions. Colombia and Uruguay have launched two pilot projects to identify and solve regional problems through interdisciplinary, cooperative participation of professionals from different countries. These programs focus on small geographical areas and their conclusions are expected to be applicable to many other places with similar problems.

The above-described approaches have proved useful to develop early warning systems based on hydro–meteorological monitoring and forecasting for precluding the consequences of unfavourable climate events (*i.e.*, to decrease vulnerability) and decrease their risk as a result.

4. Planting and harvesting changes

Modifications in seasonal rainfall patterns and the occurrence of more severe precipitation events (along with associated floods) would cause delays in both planting and harvesting. As noted in Section 1, several studies suggest that global warming and climate variability have a very negative influence on food and feed production and food security worldwide (Thornton et al, 2014; Rosenzweig et al., 2016). Climate variability is important as it often leads to droughts and decreases crop yields, and even famin in unsafe food regions (Iizumi and Ramankutty, 2015). One additional concern in this respect has arisen from the combination of climate change with population growth, dietary changes and increasing biofuel demand, all of the having negative effects (Lobell et al., 2011; Spurgeon et al., 2020).

This scenario clearly shows the importance of making sound, timely decisions on crop production. Existing gaps in this respect could be filled by considering: (a) the effect of economic conditions and access to technology on farmer responses to climate shocks; (b) the impact of extreme weather events on certain crop areas; and (c) the effects of altering work calendars and field workability to address climate impacts on crop production. Thanks to the technological expertise of local people, farmers have always understood the effects of climate on crop production very well (Iizumi & Ramankutty, 2015).

Based on the known effects of climate changes on crops, the greatest technological challenge is to detect, ascribe and understand them, to define accurate prediction models for the future (Iizumi & Ramankutty, 2015). A deeper understanding of the effects on crops by the changing climate can only be achieved by filling some knowledge gaps in knowledge worldwide. Combining indigenous, local knowledge with technological advances may be an effective way of dealing with climate change and its impacts (Painemilla et al., 2010, Cadilhac et al., 2017; Morss et al., 2011). In fact, promoting the use of indigenous knowledge to address climate-related issues [International Fund for Agricultural Development (IFAD), 2012] and their incorporation into short- and long-term plans for adaptation to the expected changes appears to be a wise strategy towards reducing uncertainties (Kangalawe et al., 2011; Cadilhac et al., 2017; Morss et al., 2011).

The above-described strategies can be supplemented with others based on innovation in planting and harvesting genomics. Some American and European countries have already diversified livelihoods, harvested rainwater or used alternative livelihoods for fishing by developing change-resistant hybrids, as a mean to face climate change, especially among farmers in diverse tropical and subtropical areas all over the world (Curcic et al., 2018). This should generate new opportunities but also lead to limitations arising from various factors of not only environmental and technological character, but also of political and market factors (Schroth and Ruf, 2014; Debaeke et al., 2017). Diversification strategies can be defined on different bases including:

- Using more profitable crops to raise income,
- Spreading income from traditional crops to shorten times between harvests,
- Increasing food security,
- Reducing vulnerability and unwanted effects on markets, policies and the environment.

4.1. Mitigation strategies

Because weather and climate changes are already here, successfully addressing them will require deriving useful insight from them by converting facts into opportunities. Some examples include the combination of local knowledge with novel innovative genomic tools and diversification; using heterogeneous site characteristics remaining as the legacy of previous forest vegetation to create new market opportunities for growing urban centers; developing effective government policies; impose restrictions to favor specific crops or facilitate access to improved vegetables or more efficient farming systems.

While diversification can respond to the problem of structural environmental degradation associated with the abuse of crop monocultures, decisions ultimately depend on farmers' conditions, such as age, educational level, economic and financial situation, as well as the dimensions of the farm and the family. Decisions can be supported by comprehensive long-term studies conducted by interdisciplinary professionals. (Schroth & Ruf, 2014).

5. Decreased arability

FAO (Nelson et al., 2009; Montanarella et al., 2015) has warned that the quality of whey is degrading under the joint effects of population growth, industrialization and climate change. Threats like erosion, depletion of nutrients and loss of organic carbon should be addressed by developing effective strategies to preserve existing cultivation areas with sustainable management practices and increase the productivity of land currently not amenable to cultivation for food production (Wagena et al., 2018; Butterbach-Bahl and Dannenmann, 2011; Chang, 2004; Hu and Buyanovsky, 2003; Kucharik and Serbin, 2008).

The international community should therefore promote sustainable land management through appropriate policies and rational investments (Mosquera-Losada et al., 2018). The increase of temperatures will shift agricultural activity to higher latitudes, where soils and nutrients are less suitable for crop production. In addition, the rise in sea level can make a number of areas currently providing substantial amounts of vegetable foods disappear, and severely impair food production and security as a result. The ensuing damage can also be expected to increase volatility in food prices on free markets, where deregulation would give way to the law of supply and demand.

The lack of nutrients in high-latitude soils is an unavoidable challenge in regions such as Finland (Peltonen-Sainio et al., 2018; Kaukoranta and Hakala, 2008) or southern Scandinavia (Aronsson et al., 2016), where it seriously hampers improvements in food production. One other side effect of reduced crop yields is accumulation of salts in cultivated soils, which makes useless for agricultural production. According to FAO's report on the status of soils (*vide supra*), about 760 000 km^2 of cropland is salinized worldwide.

There is also the acidity of arable soil layers, which can strongly diminish food production or even soil cultivation. In the short term, further degradation of soils should be avoided at all costs while the climatic conditions still allow them to be used as arable land. In the long term, effective technology to facilitate the adaptation of soils in high latitudes to crops and new cultivation techniques allowing nutrient-poor soils or even no soil to be used should be developed.

5.1. Mitigation strategies

Existing cultivated soils, including global stocks of soil organic matter, should be protected to minimize further degradation and restore productivity. In addition, it would be useful to reduce the amounts of nitrogen and phosphorus fertilizers used by employing alternative solutions in nutrient-deficient regions.

In mitigating impacts, it is important to strengthen crop resilience (Walia et al., 2018). Some authors have suggested that conservation agriculture and diversified crop rotation can help preserve food security, restore soil health and thereby minimize the potential effects of global warming (Parihar et al., 2018; Necpalova et al., 2018; Angulo et al., 2013; Burney et al., 2010; Chadwick et al., 2011). These benefits rely on the increased global potential for CO_2 sequestration of soils containing large amounts of organic C. Carbon sequestration appears to be an efficient strategy to boost agricultural production, and to purify surface and underground waters (Lal, 2004; Autret et al., 2016; de Gryze et al., 2011; Tribouillois et al., 2018).

Policies aimed at supporting the development of soil information systems should be implemented throughout to monitor and predict the changes global warming is expected to bring about in the next 50 years. This will require investing in research and development to implement and disseminate technologies and practices for the sustainable management of cultivated soils, and making the public aware of the problem through education by, for example, incorporating the issue into geology, geography, biology and economics study programs.

Issuing appropriate regulations and incentives to good management practices for cultivated soils and penalizing harmful practices to deter famers can also be very useful. Thus, introducing and consolidating certifications of sustainable agricultural practices can provide consumers with more appealing products and empower them as stakeholders of the process. As quote before, long-term measures to be taken to minimize the impact of climate change include enriching soils with organic matter. This can be accomplished by using the global reserves of organic matter in soil and transition crops to facilitate its enrichment (Kaye and Quemada, 2017).

Most of the previous examples derive from analyses and predictions for North America. In Europe, diverse studies examined the effect of global warming and climate change upon soil functions. Hamidov et al. (2018) reviewed twenty such studies and established a link to Sustainable Development Goals (SDGs). There most revealing findings were as follows: (a) adaptation options reflect local conditions; (b) reduced soil erosion threats and increased soil organic carbon are to be expected, but soil compaction may increase in some areas; (c) most adaptation options are anticipated to improve soil functions; and (d) the fact that soil functions are interrelated requires improving food security and promoting sustainable agriculture by properly addressing climate change (Hamidov et al., 2018).

6. More pests

Crop pests (insects or fungi) can survive or even reproduce with greater incidence each year as average temperatures increase in winter. Pests from lower latitudes can migrate to higher latitudes, and new pests invade other regions, as temperature and humidity conditions change. These modifications would not only be reflected on the growth of crops but also on their altitude (Battisti and Larsson, 2015; Bhatnagar et al., 2018; Bale and Haywrd, 2010; Gu et al., 2018; Castex et al., 2018). FAO convened a panel to examine the state of the art in the connections of climate change to global warming, the risks posed by pests and diseases on plants and animals, and their potential effects on human health and food security. Its members assessed the consequences of climate change on fish diseases and the behavior of invasive aquatic species, as well as the corresponding re-diffusions on aquaculture and fishing (FAO, 2008). The most salient conclusion was the presence of special risks as regards the impact of diseases and pests directly driven by climate change. This led to urge the adoption of preventive measures and the facilitation of adaptation to the challenge, as well as surveillance and control measures, together with climate-smart pest management (Heeb et al., 2019). In fact, climate change is known to be altering in a gradual but inexorable way pest distribution. Temperature and humidity changes can alter the geographical distribution of plants, fungi and insects, and hence the interaction between pests and crops. In addition, global changes in vegetation by effect of deforestation and desertification can increase vulnerability to pests and diseases. Worth special note in this respect is a growing change in geographical distribution in some arthropods (mosquitoes, flies, ticks and fleas, mainly) by effect of the changing temperatures and humidity (Sultana et al., 2017; Asplen et al., 2015). These arthropods are vectors of viruses and bacteria with implications on the health of crops and humans. As a result, new individuals without natural immunity (plants, animals and humans included) may be affected, and a public health problem or a dramatic loss of food production efficiency may arise.

Climate changes have also led a number of species to expand northwards in North America, Asia and Europe (Fält-Nardmann et al., 2018; Chen et al., 2011). This problem can have a considerable impact on aquaculture and fishing. Therefore, global warming can alter phytoplankton, zooplankton, algae and microalgae, and cause drastic changes in the geographical distribution of species. This change in geographic distribution would cause native species of certain latitudes to become invasive species by migrating to areas that are more favorable from a climatic point of view (Soto, 2008; Yanik & Aslan, 2018). The problem is worsened by the need to fight the pests with increasing amounts of xenobiotics, thus increasing the amounts of pesticide residues and veterinary drugs that penetrate the food chain to unacceptable levels (Arias-Estevez et al., 2008).

6.1. Mitigation strategies

FAO recommends using a twofold strategy based on actions to be taken on a global and regional scale, and, especially, investing substantially in improving existing early detection and control systems. This will require developing new agricultural practices, introducing other crops and animal varieties, and applying the principles of integrated pest management to help curb their spread. It may also be necessary to consider using biological agents to fight pests or using introducing pest- and diseases-resistant crops and livestock varieties. Although grain legumes possess various sources of insect resistance, widespread adoption of large-scale measures on insect-resistant crops has so far been constrained by limited efforts in the production and distribution of resistant seeds (Sharma et al., 2010). Grain legume pests can be managed efficiently through cultural manipulation and their environment through intercropping, population monitoring, modification of agricultural systems in order to significantly increase the activity of the natural enemies of a certain cultivation, the use of natural essential oils and biopesticides, either alone or in combination with traditional pesticides, cultivation of resistant varieties of insects obtained by conventional genetic reproduction or genetic engineering, and implementation of applications adapted to the specific needs of synthetic pesticides. However, the relative efficiency of some pest management strategies (particularly those based on bio-pesticides or natural plant products) may be considerably reduced by a hot climate. In addition, genotypes can be expected to interact more strongly with the medium to express resistance to pests, and this would require greater efforts in identifying sources of resistance. This would allow the development of integrated pest management packages that can be used successfully under the conditions predicted for the future.

Bacillus thuringiensis crops are plants genetically engineered to contain the endospore toxins of the bacterium, referred to as Cry toxins. Such Cry toxins are toxic to specific species of insects belonging to orders Lepidoptera, Coleoptera, Hymenoptera, Diptera, and Nematoda. In 2016, the total world area cultivated with genetically modified crops (GM crops) reached about 185 million ha, although there is a worldwide controversy about the safety of *B. thuringiensis* crops to the environment and mammals (Abbas, 2018).

It is imperative for governments to strengthen help to small farmers so that they can cope with existing impacts and build resilience to changes. Some authors (Harvey et al., 2018) have underlined the capital need to make adjustments on climate adaptation policies and programs focusing on various socio-economic conditions, different biophysical contexts and various climatic tensions, with special emphasis on small and medium farmers. One of the most promising initiatives in this context was the program “Allied Insects”, which used insects containing certain viruses as vectors to help crops fight threats such as drought or pollution (Ford et al., 2010). CRISPR-based gene drives have been proposed as a way to reduce or eliminate insect-borne diseases, control invasive species and even reverse insecticide resistance in pests, but researchers worry about the consequences of unleashing this new technology (Champer et al., 2017). Reeves et al. (2018), however, have recently questioned the program, in such a prestigious journal as Science. These authors suspect that the US Defence Advanced Research Projects Agency (DARPA) may somehow have funded the project to breach existing international treaties against the proliferation of biological weapons established in the Biological Weapons Convention (BWC).

7. Risks to fisheries

Aquaculture and extractive fishing contribute substantially to food security and the livelihoods of millions of people worldwide. The combined global production of both sectors was quantified at 171 billion kilograms in 2016, with 53% and 47% from extractive fishing and aquaculture respectively (FAO, 2018a). A value of € 323 billion has been estimated, 207 billion of them coming from aquaculture (FAO, 2018a). Growth in aquaculture production was largely responsible for the average annual increase in world fish consumption from 1961 to 2016: 3.2%, which was twice the growth rate of the human population (1.6%). Fish consumption per capita increased globally from 9.0 kg in 1961 to 20.2 kg in 2015. This economic activity, combining both sectors, directly or indirectly employs some 200 million people (Movilla-Pateiro et al., 2020).

Food security and livelihoods associated with activities related to extractive fishing and aquaculture are key to numerous coastal, river, island and inland areas. However, we must bear in mind that the status

Table 1
Emerging food risks examples affected by climate change.

Emerging risk	Food sector	Category	New risk factor	Identifying body	Recommendations	References
Risk of grain price rises due to decreased production by effect of climate change	Products from grains	Socio–economic	Climate change	Intergovernmental Panel on Climate Change (IPCC) 2007	Controlling greenhouse gas emissions	Lake et al. (2012)
Risk of food contamination	Agriculture and food industries	Microbiological	Climate change. Increased incidence of contamination by *Salmonella*, and *Campylobacter*	UK	Horizon scanning or real time food early warning systems	Lake (2017)
Risk of increase in pathogens with low infective doses (parasites) favoured by climate change		Microbiological	Climate change	UK	Importance of epidemiological surveillance. Developing methods for the rapid detection of pathogens	Cable et al. (2017)
Risk of increased incidence of infectious diseases		Microbiological	Climate change	Competent bodies for scientific advice on infectious diseases	Address deficiencies in institutional capacity to manage vulnerability to climate change in impact, and adaptation assessments.	Semenza et al. (2012),
Microbiological risk associated to fresh products	Fresh food	Microbiological	Climate change Globalization		Simulation of climate change scenarios and fresh goods logistics chain. Mathematical models to optimize packaging technology in order to maintain the quality and safety of fresh products	Jacxsens et al. (2010)
Risk of presence of toxic metals, residues of organic chemicals and toxins in seafood	Fish, seafood, seaweed	Chemical	Climate change		Making public health authorities aware of the new challenges to assure safety in sea products	Marques et al. (2010)
Risk of increased parasitic diseases in aquatic animals	Aquatic products	Microbiological	Climate change		Acknowledging the biological significance of each disease. Considering the role of local conditions to determine the direction and magnitude of the effects	Karvonen et al. (2010)
Risk of ocean acidification	Fish, seafood, seaweed	Microbiological	Climate change		Inter-sector and international cooperation to better understand the changing situation of food safety. Developing and implementing adaptation strategies	Tirado et al. (2010)

of resources, monitored by FAO, continues to decline. Although fisheries substantially contribute to the global demand for food (especially in poor countries, with greater food insecurity), the lack of data on the status of many fisheries in inland waters leads to a more delicate situation. All this demonstrates the great importance of responding efficiently and effectively to the crisis associated with global warming: not only fisheries are essential for food, livelihoods and trade, but also the generally poor state of resources restricts their ability to absorb climatic shocks (Barange et al., 2014). Also, commercial fishing will be significantly affected due to changes in abundance and in fish and other shellfish species.

The ocean makes up 71% of the planet and provides many services to human communities from mitigating weather extremes to generating the oxygen we breath, from producing the food we eat to storing the excess carbon dioxide we generate. However, the effects of increasing greenhouse gas emissions threaten coastal and marine ecosystems through changes in ocean temperature and melting of ice, which in turn affect ocean currents, weather patterns, and sea level. Extreme ocean temperatures and ocean acidification endanger coral reefs, the foundations of many fisheries, also modifying the quantity and quality of phytoplankton and zooplankton, and dramatically affecting the entire food chain.

7.1. Reducing carbon emissions by fishing industries

Global fish production from capture and culture operations also contribute for the global CO_2 emissions (Parker et al., 2018). Although overall fish production is relatively energy-efficient relative to other high-quality animal protein production on land, there is still place for further reduction in energy use and gas emissions (FAO, 2018b).

The vessel and gear used in capture fisheries are two major users of energy. Thus, in stationary gear fisheries, vessels travelling to and from fishing grounds often use large amounts of energy, and so does resistance from the fishing gear in mobile gear fisheries of the trawling or dredging type. Shore-side facilities should take advantage of maturing renewable energy systems such as those based on wind and solar power. In aquaculture, intensive production of finfish and crustaceans, which relies heavily on feeds and aeration, is the greatest source of greenhouse gas emissions. Integrated food production systems such as those of fish and rice or shrimp and mangrove can substantially reduce such emissions from aquaculture systems (Badiola et al., 2018).

Fishery management has a strong impact on all aspects of fish production (especially in capture fisheries), and can thus influence fuel use efficiency. In addition, fuel subsidies intended to support fisheries have usually deterred promotion of fuel-efficient vessels, gears and operations. Management measures reducing overall fishing efforts and improving stock abundance (*e.g.*, individual harvesting quotas and similar rights-based regimes) have proved useful to increase fuel efficiency in capture fisheries. In any case, fuel use efficiency and greenhouse gas emissions from fisheries should be considered an integral part of fishery management to assure sustainability.

7.2. Mitigation strategies

Climate change have significant impacts on freshwater and marine aquatic systems and hence on fisheries and aquaculture (Peeler & Ernst, 2019). Fisheries and aquaculture are highly vulnerable to changes in temperatures, flooding, droughts, rises in the water levels, among the most important ones. The impacts of such events affect fish population, production and supply, thereby affecting the livelihoods of people engaged in the primary and secondary sectors of the fisheries industry, as well as food security. The adaptation and mitigation strategies are based on the peculiar characteristics and interactions of fisheries and aquaculture within the framework of feasible policy instruments. Strategies and policy measures need to be evolved to combat the observable and projected impacts of climate change on fisheries and aquaculture in order to protect the livelihoods of the fishing communities and food security. The response will depend mainly on the characteristics of the fisheries and the adaptive capability of the communities. However, each country needs adaptive and mitigation strategies that will improve the management of the fisheries and aquaculture, protect the integrity of the aquatic ecosystems, respond to the opportunities and threats on livelihoods and food security and reduce greenhouse gas emissions (FAO, 2018a,b).

8. Emerging food risks

A need currently exists to develop a food system-based approach integrating the social sciences to improve our understanding of interactions and dynamics between stakeholders and drivers, and to develop horizon-scanning protocols (Table 1). This will require improving data processing pipelines in order to prepare big data analytics, implement data validation systems and develop data sharing agreements to explore mutual benefits, increase transparency and improve communication.

8.1. Mitigation strategies

Existing guidelines for food control remain valid in the face of the potential additional challenges posed by climate change-related phenomena (FAO/WHO, 2006). Different issues are particularly relevant in order to identify emerging risks as soon as possible. Such issues are detailed explained below.

8.1.1. Interdisciplinarity

Food safety involves the whole process of food production, from pre-production to the final product. Therefore, food safety assurance is a complex task. Recommendations associated to food safety generally underline the necessity of an extensive input and coordination, and this is a challenging task in many countries. Animal and plant health, environment and food hygiene are interconnected aspects expectedly affected by climate change. Therefore, food safety challenges involve a preparation and understanding in an interdisciplinary context. Furthermore, the large implications of climate change on public health and food safety have complex consequences (Schnitter and Berry, 2019).

8.1.2. Application of good practices

The national programs of good practices on hygiene, agriculture, animal husbandry, veterinary care and aquaculture are crucial for defining management strategies towards climate change. Nevertheless, such guidelines have to be engineered taking into account the impact of changes on the prevalence and occurrence of microbiological and chemical hazards, as well as on insects, pests and their vectors. The development of guidelines on these issues requires the development of high standard applied research to support the different approaches proposed to solve the problem. To this aim, a continuous update of guidelines is crucial, as soon as novel knowledge is created. However, for a successful implementation of this, a compromise of governments and industrial associations is a determining factor.

8.1.3. Monitoring and surveillance – Food and the environment

An early identification of potential problems entails an integrated monitoring of both food and environmental changes because it enables the implementation of solutions. Although such programs are implemented in different countries, such surveillance requires a continuous revision of emerging hazards associated to global climate change. The data produced by such programs can be very useful to improve predictive modelling and risk assessment, so they should be easy to share nationally and internationally. At an international level, relevant information can be circulated through networks such as INFOSAN (the International Food Safety Authorities Network). This network provides a mechanism for exchanging information on routine and emerging food safety issues. A need clearly exists to focus research efforts on the development of expeditious methods for detecting pathogens and contaminants in complex sample matrices such as foods in order to facilitate a rapid response to the results of monitoring and surveillance programs (https://www.efsa.europa.eu/en/cross-cutting-issues/networks).

8.1.4. Disease surveillance – Human and animal

Monitoring the epidemiology is critical in public health, not only for an early identification of emerging diseases, but also to implement strategies for their control. For this reason, an efficient epidemiological monitoring requires a close collaboration of professionals dealing with human and animal health, as well as those focused on environmental issues. In this regard, a quick investigation of unusual outbreaks is critical. The International Health Regulations provides a management program for coordinating events associated to climate change that could lead to international health emergencies, also providing assistance for their detection, notification. One Health is an emerging global key concept integrating human and animal health through international research and policy. The complex relationships between the human and animal have resulted in a human-animal-environment interface since prehistorical times. People, animals, plants, and the environment are so intrinsically linked that prevention of risks and the mitigation of effects of crises that originate at the interface between humans, animals, and their environments can only improve health and wellbeing. The "One Health" approach has been successfully implemented in numerous projects around the world. The containment of pandemic threats such as avian influenza and severe acute respiratory syndrome within months of outbreak are few examples of successful applications of the One Health paradigm (Shrestha et al., 2018).

8.1.5. Predictive modelling

Different predictive models have been developed to foresee the probability of a given outcome to occur. Some of the have been defined to evaluate how the climate change can affect ecological systems and lead to emerging hazards. The marine sector has used such models in combination with meteorological, oceanographic and remote sensing information to predict harmful algal blooms (Shutler et al., 2012). Because accuracy in the predictions depends on the amount of data available and on their quality, international collaboration is essential in developing accurate models. In addition, as climate-associated changes are the more and more complex, the development of predictive models requires sustainable accomplishments and continuous international cooperation.

8.1.6. Risk assessment

Risk assessment gives a scientific background to develop and adopt food safety standards, as well as other food safety actions. The effects of climate change can lead to novel food safety risks, which in turn determine novel priorities in risk assessment. For instance, if mixtures of mycotoxins appear more frequently in crops, then the maximal accepted concentrations should be revised. New mycotoxin occurrence frequency and level data from monitoring and surveillance programs could also influence decisions on appropriate limits at the national or international level. A group of Joint FAO/WHO experts has set up risk assessment on contaminants, pesticides, veterinary drug residues, food additives and microbiological hazards. Furthermore, another group of experts from Joint FAO/WHO was designated to deal with emerging issues as they arise. All the countries members of WHO and FAO can propose the prioritization of risk-assessment at an international level (FAO/WHO, 2007). Moreover, these countries have access to risk assessment guidance on emerging hazards arising from climate change.

International risk assessment mechanisms should be established and experts trained in developing countries to understanding how risks must be assessed in order to make informed decisions on their local applicability in the light of new data obtained from their own monitoring and surveillance programs.

8.1.7. Early warning and emergency response systems

Improved early warning systems are fundamental to reduce the risk posed by climate change-related natural disasters and emergencies on the lives and livelihoods of vulnerable people. This requires close cooperation among the veterinary, food safety and public health sectors at both the national and the international level. Emergency preparedness is also essential. Countries should review their existing food safety emergency plans and develop new ones. They should review and update other disaster and emergency plans to ensure that food safety management issues are appropriately dealt with in those situations (Tirado et al., 2010; Watts et al., 2018).

8.1.8. Strengthened dialog with the public

Food safety should be assured through effective control measures at every step along the food chain (Zwietering et al., 2010). Since one-third of food produced in developing countries is lost before consumption, and due to high moisture contents in storage promote spoilage and production of mycotoxins, the "dry chain", which is initial drying with storage in water-proof containers, is proposed as an effective control technology (Bradford et al., 2018). Other new drying and storage technologies make implementation of the dry chain feasible to minimize mycotoxin accumulation and insect infestations in dry products, reduce food loss, improve food quality, safety and security, and protect public health.

If consumers are to play their intended role, they should be aware of the hazards associated with some foods and of the relevant control measures. Consumers' education is therefore essential and governments have a role to play here. The public does not properly understand some hazards, such as those posed by mycotoxins, as they represent an essentially invisible threat that is difficult to publicize effectively. Informing the public about typical foods susceptible to mycotoxin contamination, and about their risks to public health, might help reduce the use and trade of substandard food in hard times.

8.1.9. New technologies

A number of scientific and technological innovations are expected to play a major role in helping us understand and deal with the food safety challenges posed by climate change. Such innovations include new, nano-based filtering devices capable of removing a wide range of chemical and microbiological contaminants from water or even soils (Guerra et al., 2018). They also include rapid pathogen and contaminant detectors relying on novel techniques (nanotechnologies included); new molecular biological methods such as nucleic acid sequence comparisons and genomics-based approaches to characterizing complex microbial communities and their interactions; and the use of genetically modified crops suitable for growth on marginalized land. Although countries will differ in their capacity to participate in the development of the new scientific and technological advances, all should strive to be up to date with new developments so that they can efficiently exploit the new opportunities and, possibly, influence the prioritization of research investments. Special attention should be given by each individual country to the development of capacities and mechanisms for assessing and managing environmental and food safety risks potentially associated to the use of the new technologies. As noted above, FAO/WHO continue to develop guidance on genetically modified food safety assessments. In addition, they intend to hold an expert meeting on the potential food safety implications of nanotechnology applications in the food and agriculture sectors.

8.1.10. Investing in scientific and technical capacities

Some of the above-discussed issues share a common theme, namely: the need for applied research to provide a better understanding of problems and for new approaches to dealing with them. The ability to use science to find solutions relies on prior investments in developing human resources. Many developing countries will require more careful planning to encourage the development of the competence needed to address pressing problems. In many cases, it is already possible to make better use of existing competence at the national level by fostering relationships among government services, universities and private sector associations, among others. Carefully assessing food safety capacity building requirements by national authorities is also essential for optimal training and education through technical assistance from interested donors and international organizations (Mahmoud, 2019).

8.1.11. International dimension

The whole issue of climate change is a global concern (Esteki et al., 2019), so international bodies should play a major role in assuring that all of its dimensions are properly dealt with (Galvez et al., 2018). As noted earlier, a need exists to share data and information obtained from food safety and disease monitoring and surveillance systems that international networks could help fulfil. Regional and international cooperation on selected research areas of common interest would probably afford better outputs from existing resources. The international community should have timely access to scientific advice to guide their management choices as new food safety risks emerge. Since climate change can cause food safety risks to occur, it would be useful to devise ways to make mechanisms for providing scientific advice more responsive to increased and unscheduled demands. The Joint Global Initiative for Food-Related Scientific Advice (GIFSA), which was jointly established by FAO and WHO, should address this need at least in part. GIFSA aims to facilitate transparent fund mobilization to facilitate the organization of expert meetings on critical food safety issues requested by Codex or by FAO and WHO member countries. The food safety challenges raised by climate-related changes have highlighted the need for continued emphasis on food safety capacity building in developing countries. Coordination among donor agencies and international organizations providing technical assistance in this area remains a central issue.

9. Effect of climate change on hunger, food security and nutrition

FAO sees no progress in Sustainable Development Goals (SDGs); the efforts for sustainable farming, together with the long-term management of land and ocean-based resources, were unsuccessful (United Nations, 2019). More than 820 million people are hungry around the world. About 60% of all livestock breeds are at risk of extinction, and little is done to conserve DNA from plant species at the greatest risk. Also, one-third of all marine stocks are currently overfished. All continents are under water stress, especially in Northern Africa and in Western, Central or South Asia.

9.1. Mitigation strategies

Measuring SDG indicators is an enormous task (FAO, 2019a). To alleviate the associated problems, FAO has launched a systematic capacity development programme comprising regional training workshops, technical assistance missions and e-learning courses. However, data for a number of specific SDG indicators in terms of country coverage, data points per country or both are still limited. No globally comparable data exist for four critical indicators pertaining to agricultural sustainability, women's access to land, and food losses, and waste. The lack of reliable information has not only deterred countries from implementing effective food and agriculture policies, but also hindered development of international cooperation efforts. Very few countries perform farm or household surveys, compile forest inventories or assess fish stocks. In addition, they often fail to obtain the data needed for key food and agriculture-related indicators, which could be easily upgraded to broaden country coverage in reporting on SDGs. In some cases, the data needed to compile indicators are available but not reported to FAO on a regular basis. To alleviate these shortcomings, FAO recently launched a multi-donor programme with USD 21 million to expedite support for the collection, production, dissemination and use of all 21 SDG indicators under its supervision.

10. Conclusions on the impacts of climate change on food systems

Although agriculture has always been at the mercy of unpredictable weather, today is even more vulnerable. Warmer temperatures may increase crop yields in some regions, but climate change is expected to have adverse overall impacts leading to reduced food supplies and increased food prices (Nelson et al., 2009). Sub-Saharan Africa and South Asia are already experiencing high rates of food insecurity, and are predicted to see the greatest declines in food production (Schmidhuber & Tubiello, 2007; Nelson et al., 2009; Gornall et al., 2010). Elevated levels of atmospheric carbon dioxide are expected to lower the levels of zinc, iron and other important nutrients in crops (Myers et al., 2014). With changes in rainfall patterns, farmers face dual threats from flooding and drought. Flooding washes away fertile topsoil on which farmers depend for productivity, whereas droughts dry soil out and make it easier to blow or wash away. Elevated temperatures increase the water requirements of crops and make them more vulnerable in dry periods (Nelson et al., 2009).

Some species of weeds, insects and other pests benefit from elevated temperatures and carbon dioxide levels, which increase their potential to damage crops and create financial hardship among farmers. A shifting climate also facilitates expansion of agricultural pests to new areas (US Global Change Research Program, 2009). With higher temperatures, most of the world's glaciers have begun to recede; this has affected farmers who depend on glacial melt water for irrigation (IPCC, 2013; 2014a). Rising sea levels are increasing flood risks for coastal farms and boosting salt-water intrusion into coastal freshwater aquifers —thus making these water sources too salty for irrigation (Backlund et al., 2008).

Climate change is also expected to have an impact on ecosystems and the services they provide to agriculture (*e.g.*, pollination, pest control by natural predators). Many wild plant species used in domestic plant breeding are threatened by extinction (Jarvis et al., 2010). Food system activities, including food production and transport, and food waste storage in landfills, produce greenhouse gas emissions that contribute to climate change. Livestock, which is the greatest contributor, accounts for an estimated 14.5% of global greenhouse gas emissions from human activities (Gerber et al., 2013), and meat from ruminants is especially emission-intensive (Tilman & Clark, 2014).

World leaders have agreed that the average global temperature should not rise by more than 2 °C above pre-industrial levels if the most catastrophic climate change scenarios are to be avoided. Even if this goal is fulfilled, many climate impacts such as sea level rise are likely to remain for centuries (IPCC, 2014b). Imagine a scenario in 2050 where societies have transitioned away from coal and natural gas to wind, solar and other renewable sources of energy. In this scenario, public policy and infrastructure investments will have turned walking, cycling and public transit the most accessible and popular forms of transportation and air travel will be used only as a last resort. In this otherwise best-case scenario, if global trends in meat and dairy intake continue, our likelihood of staying below the 2 °C threshold will still be extremely low (Kim et al., 2015). This is why urgent, dramatic reductions in meat and dairy consumption, together with substantial reductions in greenhouse gas emissions from energy use, transportation, and other sources, are crucial to avoid catastrophic climate changes. The responsibility for eating lower on the food chain falls most heavily on countries such as the US, which is the greatest per capita consumer of meat and dairy. Changing diets on an international scale will require more than simply re-educating consumers; in fact, national policies will have to provide increasing support for plant-centric diets (Kim et al., 2015). Strategies for improving resilience to climate change and extreme conditions should be anticipated in all production management areas (Table 2).

Table 2
Strategies for improving resilience to climate change and extreme climatic conditions.

Problem	Strategy
Raw crop management	Breeding for drought and temperature tolerance
	Earlier planting
	Increasing the organic content of soils
	Using conservation tillage or no-till to decrease run-off and increase infiltration
	Establishing and maintaining buffers, filter strips and grassed waterways near water sources
	Shifting to less water-dependent cropping systems
Livestock management	Selecting breeds and types
	Improving nutritional management during periods of high heat load
	Sun-shading, evaporative cooling, mechanical ventilation
	Using rotational grazing systems to minimize damage to range and pasture
	Active management of forage stocks and reduced herd sizes under droughts
Water management	Installing more efficient irrigation systems or making existing systems more efficient
	Water storage in ponds and tanks
	Rational management of water use
	Installing watering facilities to ensure that livestock have access to water
Improving access to information	Using early warning systems for droughts
	Research and development
	Developing programs to help farmers manage risk
	Fostering regional outreach, extension and education

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