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REVIEW ARTICLE

Potential impacts of climate change on agriculture - A review

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ABSTRACT

Greenhouse gases content in the atmosphere significantly raised since the beginning of the industrial revolution, mainly associated to anthropogenic emissions, namely those related to altered land use. Such rise is driving changes in the climate, which will worsen throughout the 21st century. Agricultural systems are particularly vulnerable to Climate Changes (CC) thus the attempts to achieve higher crop productivities, simultaneously with more efficient use of resources, while minimizing environmental impacts could fail. The CC mitigation/adaptation measures require a major effort to decarbonise the economy, which includes a global greenhouse gas emissions reduction of *ca.* 50-60% by 2050, as compared to 1990. These actions should be used in a complementary manner, in order to greatly reduce the vulnerability of agri-food systems, thus, contributing to food security and safety. The water shortage and increase of extreme events episodes in Southern Europe may lead to abandonment of agricultural practices, whereas in the northern Europe it is foreseen the expansion of suitable crop´s areas and yield increases, thus emphasizing that the estimated impacts of climate changes will not be uniform throughout the world.

Keywords: Adaptation; Drought; Global warming; Mitigation; Sustainability

INTRODUCTION

Climate changes (CC), particularly those related to global warming, are nowadays widely discussed on a global scale, being already an indisputable reality according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014). Since 1950's, a greater incidence of extreme weather events worldwide was observed, with impact on human and natural systems. The continuous increase of greenhouse gases (GHG) emissions is pointed to be responsible to further warming, changing most components of the climate system, and leading to a greater probability of severe and irreversible impacts on populations and ecosystems (IPCC, 2014).

Worldwide extreme events, such as heat and cold waves, severe droughts and heavy rainfalls, underlines the high vulnerability of agricultural systems. Global warming impacts can already be observed, namely reduced snow and ice areas and rising sea levels. Moreover, estimated future CCs are believed to additionally amplify the existing climate-related risks and create new ones (IPCC, 2013; Semedo et al., 2018). In fact, temperature and rainfall regimes showed increased instability and unpredictability, with main concerns related to the occurrence of extreme events which became more pronounced and frequent. For example, the heat wave that hit Western and Central Europe in the summer of 2003 led to average temperatures in June, July and August, 3.8 °C above the values found for the period 1961-1990, supporting the view of a global warming trend (Luterbacher et al., 2004).

Several authors point that global warming has now, and will have a growing impact on Earth's ecosystems,representing

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a serious threat to agricultural sustainability (Xu et al., 2013; Beach et al., 2015; Tack et al., 2015), although agriculture is responsible for *ca.* 1/3 of CO_2 emissions through N_2O and CH_4 (van Beek et al., 2010). The increase of agricultural productivity in an environmentally sustainable way, in a context of CC, is a huge challenge (Semedo et al., 2018), even more because global food security may be at risk (DaMatta et al., 2010). The current world population is expected to increase from 7.6 to 9,800 million people by 2050, boosting demands for energy and food (FAO, 2009; 2011). In this context, global food production should increase by *ca.* 60-70% (Powell et al., 2012; FAO, 2016), including staple crops by *ca.* 43% (Powell et al., 2012).

Studies examining a wide range of regions and crops reported that negative impacts of CC on crop yields have been more frequent than positive impacts. The later occur almost exclusively in high-latitude regions (IPCC, 2014). Plants have quite narrow optimum cultivation conditions that allow to obtain better yields while maintaining the quality (Zullo et al., 2011; Tozzi and Ghini, 2016). The enhancement of air [CO_2] affects fundamental plant processes, such as photosynthesis and respiration, thus with the potential to alter (enhancing) plant growth (Lee et al., 2015; Martins et al., 2016; AbdElgawad et al., 2016; DaMatta et al., 2018). Still, the enhancement of air CO_2 *vs.* temperature increase interaction is quite complex, and should be considered for each crop/genotype. In fact, increases in CO_2 levels to 600-700 ppm was reported to stimulate liquid photosynthesis in C3 plants, often to values 50% above of the actual ones, with a higher positive impact at higher temperatures, thus contributing to reduce or cancel the expected negative impacts of temperature rise (Kirschbaum, 2011; Rodrigues et al., 2016). That was the case reported for the coffee plants, which showed that an increase of [CO_2] to 700 ppm canceled the negative effects of high temperatures on the coffee bean (Ramalho et al., 2018), and on leaf physiology, the latter linked to the reinforcement of defense mechanisms (Martins et al., 2016; Rodrigues et al., 2016). Furthermore, elevated [CO_2] also clearly mitigates the impact of drought on the photosynthetic functioning in *C. arabica* L. (Avila et al., 2020). In fact, contrary to earlier reports using modelling approaches that estimated dramatic impacts on the coffee crop yield and suitability of cultivations areas (Assad et al., 2004; Bunn et al., 2015), the coffee production was recently estimated to suffer no effect or even an increase in production under elevated air [CO_2], given that water availability is guaranteed (Verhage et al., 2017; DaMatta et al., 2018; Rahn et al., 2018). Still, the impact in the reproductive structures are still to be determined under the concomitant exposure to warming and elevated air [CO_2], in order to guarantee this crop resilience and, thus, sustainability (Dubberstein et al., 2018; Semedo et al., 2018). Therefore, it is clear that such kind of impacts and plant acclimation responses needs a stronger research effort regarding the main crops, in order to guarantee an adequate food and feed supply.

Future climate will be closely dependent of GHG emissions and, thus, of the strategies and will to limit such emissions. The global increase of mean air temperature by the end of the 21st century is expected to fall within the range between 0.3 and 4.8 ºC, depending of the emission scenarios. The greater the temperature rise, the worst will be the extreme weather events in frequency and severity, which, will include changes in the intra- and inter-annual precipitation patterns, with longer periods of drought and heavy rainfall events, and the melting of glacial ice and the sea level rise (IPCC, 2014).

Accordingly, in different regions, livestock production is already suffering from the negative effects of CC (IPCC, 2014). Among these, the competition for natural resources, negative impact on quality and amount of feed crops and forage, water availability, increase in livestock diseases, as well as reproductive and biodiversity reductions (Rojas-Downing et al., 2017). At the same time, the livestock sector contributes with 14.5% of the annual total GHG emissions (Gerber et al., 2013), and is responsible for soil degradation, air and water pollution and loss of biodiversity (Steinfeld et al., 2006; Reynolds et al., 2010; Bellarby et al., 2013).

In the future, the foreseen CC would increase some climate-related risks and generate new ones (IPCC, 2013). To address CC, agriculture, forestry and fisheries must accept and promote climate-friendly practices. Agriculture, which has always been the interface between natural resources and human activity, is nowadays crucial to solve some of the greatest mankind challenges, associated to eradication of hunger and poverty, while maintaining stable climate conditions (FAO, 2016).

GENERAL IMPACTS OF CLIMATE CHANGES

In the past, CC already caused disturbances on natural and human systems, with a societal collapse associated with regional severe droughts that promoted the decline of the Maya civilization in Mexico. Decreases in daily temperature ranges in many areas, with night minimum temperature increasing more than diurnal maximum temperature, increases in the frequency, magnitude, and duration of climate-related extremes, such as, heat waves, strong rainfall, tropical storms, cyclones and wildfires, floods, as well as an increase of regions affected by droughts, are already occurring (Wassmann et al., 2010; IPCC, 2013).

Current climate variability might lead to disruption on food production and water supply, with negative outcomes for crop yield, price increase and food insecurity, enhancing the vulnerability of human systems. Changes in precipitation or melting snow and ice (*e.g.*, permafrost warming and thawing), can interfere in many regions with hydrological systems, with impact on the amount and quality of available water resources (IPCC, 2014). According to the Australian Academy of Science (https://www.science.org.au/learning/general-audience/science-booklets/science-climate-change/7-what-are-impacts-climate-change) the impacts of CC in Australia are associated with rising temperatures and increases in the number, duration and severity of heat waves. This will alter the growth and distribution of plants, animals and insects, promote the shift in the distribution of marine species and increases in coral bleaching on the Great Barrier Reef and Western Australian reefs. In what regards Europe (https://ec.europa.eu/clima/change/consequences_en) Southern and Central Europe are experiencing greater frequencies of heat waves, and droughts, associated with forest fires. That is the case of the Mediterranean region, which is becoming drier, what turn it even more vulnerable to drought and wildfires. On the other hand, Northern Europe is getting significantly wetter, and winter floods could become common. Finally, urban areas, are exposed to heat waves, flooding or rising sea levels, and are often insufficiently equipped for adapting to CC. Data from NASA show that Greenland lost *ca.* of 281,000 million tons of ice per year on average between 1993 and 2016, while Antarctica showed a reduction of *ca.* 119,000 million tons per year during the same time period, but with an increasingly tripled mass loss since 2012, as compared to the previous period (https://www.jpl.nasa.gov/news/news.php?feature=7159).

In plants, the basic metabolic pathways of photosynthesis and respiration are among those that show high sensitivity to warming (Song et al., 2014). High temperatures can reduce stomatal conductance, thus, the diffusion of gas through mesophyll, and light energy use, while it impact chloroplast ultrastructure (Wise et al., 2004; Wahid et al., 2007; Santos et al., 2015). In this context, supra-optimal temperatures will have a direct impact on C-assimilation, and in the carbohydrate availability for energy and to support plant growth (Song et al., 2014). Moreover, negative effects of heat stress are also frequently related to protein denaturation and aggregation, being frequently associated as well to an increased accumulation of reactive oxygen species (Suzuki and Mittler, 2006; Hasanuzzaman et al., 2013), and even ethylene synthesis (Djanaguiraman and Vara Prasad, 2010). In this context, warming can affect crop development from sowing to grain maturity (*e.g.*, in cereals), including flower set and grain-filling stages, which are of crucial importance to the obtained yield (Barnabás et al., 2008). Higher risks are likely expected if water shortage will arise concomitantly with the temperature increase. Impacts will strongly vary across regions according to differences in biophysical resources, management, and other factors. Without appropriate adaptation measures, South Asia and Southern Africa will likely suffer severe negative impacts on a number of important food crops, what might implicate changes to less impacted crops as a viable adaptation option (Lobell et al., 2008).

IMPACTS OF CLIMATE CHANGE ON AGRICULTURE AND FOOD SECURITY

Food security is considered to exist when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and preferences, enabling an active and healthy life (World Food Summit, 1996). Actually, significant impacts of CC on agriculture and food security are a new reality, making imperative that farmer, shepherd, fisheries and forest sectors and enterprises can gain access to technologies, markets, information and credit to adjust production management systems and practices (FAO, 2016). Since food production depends directly on natural resources, which are closely dependent to climate and weather conditions, increasing food production in a CC scenario is a complex challenge (FAO, 2016) that might well affect the livelihood of populations. Due to CC, the geographical shift of major field crops is probable to take place in a near future, as well as a decrease in useful insects (Singh and Reddy, 2013). This could lead to the need for a new “agricultural revolution”, since it is necessary to feed a growing population (Reynolds et al., 2010). By 2050, FAO expects that global food demand increase by at least 60% above 2006 levels, therefore demanding a deep worldwide transformation of agriculture systems for food and feed production (FAO, 2016).

Previous studies suggest that CC effects are regionally differentiated, especially in agricultural production, so that some crops are already at risk. A 5-7% yield decrease on several important crops (including cereals) is expected with 1 ºC increase (Wassmann et al., 2010; Sultana et al., 2009), and may exceed 15% in wheat, with a 2 ºC increase (Ahmad et al., 2015), even considering that some new cropping areas may become available. The limitation of global warming to a maximum of 2 ºC relative to pre-industrial levels is considered the value above which there is a risk of global and multiple environmental impacts, namely in agriculture, availability of water resources, forests, ecosystems and human health. The international community made joint efforts to maintain global warming below 2 ºC through the Paris Treaty, taking responsibility for building a sustainable future for mankind.

Impacts in europe

The European Environment Agency (EEA) report refers to ten important natural-hazards for Europe related to CC (EEA, 2017). Over the past decades, Europe has experienced many summer heat waves, droughts, forest fires, concentrated and heavy rainfall events leading to floods and landslides, windstorms and hailstorms. These events have most important impacts on human health and economy, as well as in ecosystems, and are amplified if combined with other changes, such as increased soil sealing, construction in risk-prone areas, aging populations and ecosystem degradation. Still according to the EEA, in the European Economic Area, the total economic losses was over 450,000 million € in the 33 member countries over the 1980–2016 period, associated to floods (40%), storms (25%), droughts (10%) and heat waves (5%).

Increases in air temperature, were associated to the advance of flowering by *ca.* two days per decade over the last 50 years in several crops. Other, phenology changes, namely the reduction of the grain-filling phase duration of cereals and oilseed crops, are also affecting negatively crop production (EEA, 2017), although such impacts could significantly differ across the European regions. In fact, Northern Europe will benefit of longer growing seasons and an extension of the periods with positive and adequate temperatures, what will turn possible to cultivate new areas and crops. On the other hand, heat waves, together with decreased rainfall amounts and water availability, are expected to hamper crop productivity in Southern Europe (IPCC, 2014). In some parts of the Mediterranean region, the extreme heat and drought conditions in the summer months, might implicate that summer crops may be grown earlier in winter. Other areas, such as Western France and South-Eastern Europe, will likely face yield reductions due to hotter and dryer summers, however without the possibility of shifting crop production into winter (EEA, 2015).

As referred above, the impacts of CC are not uniform all over Europe and the last outlook point to substantial differences among different regions. For example, in the Iberian Peninsula (Portugal and Spain) hot and dry conditions reduced yield expectations for the main winter crops and spring barley whereas the lowering of water reservoirs might lead to restrictions on water use for irrigation of summer crops (JRC MARS Bulletin, 2019). Conversely, abundant rainfall in Italy and Southern central and Eastern Europe is beneficial for summer crop's growth. Furthermore, forecasts for grain maize and sunflowers are clearly above the five-year average, as a result of the favorable conditions in large parts of South-eastern Europe.

The diversity of native species and plant communities of European oceanic regions can be threatened by CC, with emphasis regarding arctic-montane and boreo-arctic montane species, which are expected to become highly vulnerable species in Ireland. For instance, the relatively small extent and low altitude of Ireland's mountain areas will implicate that the many species of these communities have little chance of shifting their range to areas of suitable climate (Hodd et al., 2014), what underline the need to adopt conservation strategies.

Another important aspect of tackling CC is the perception of farm-holders and policy-makers. Through questionnaires in 26 countries encompassing 13 Environmental Zones, it was concluded that farmers are already adapting to CC, mainly by changing the timing of cultivation and through the selection of new crop species and/or cultivars, despite some negative expectations (Olesen et al., 2011). The most negative effects of increased heat waves and droughts were found for the continental climate in the Pannonian zone (Hungary, Serbia, Bulgaria and Romania), without possibilities for an effective shif of crop cultivation to other parts of the year.

How to accurately access the economic impact of CC on agriculture productivity, with gains in the North and clear losses in the South is quite difficult, with variables often ignored such as inter-annual price fluctuations. Nevertheless, we must emphasize the PESETA and PESETA II Models (Ciscar et al., 2012; 2014) indicating that the Europe GDP will be reduced by 3% (Ciscar et al., 2012), while the estimated climate related cost for agriculture of €18,000 million/year in Europe by the 2080s, driven by yield reductions in Southern Europe. In the short-term, adaptation measures could mitigate yield reductions for all regions of Europe, except Iberian Peninsula (Ciscar et al., 2014).

Impacts on the tropical region

Tropical regions are highly vulnerable to CC and food insecurity, with the greater need for agricultural system adaptation (FAO, 2016). Sub-Saharan Africa are facing recurrent food and water scarcity crises, which have been triggered or exacerbated by climate variability, affecting agricultural productivity and food security of rural households (Haile, 2005). Long-lasting food insecurity will likely increase in the near future, accompanying an expected fivefold rise demand of food products by 2050 (Sultan and Gaetani, 2016). Similar to West Africa, warming is expected to cause a loss of income (Sultan and Gaetani, 2016) in East and Southern Africa, North and South India, Southeast Asia, Northern Latin America and Central America (Ericksen et al., 2011). A range of less than 120 days growth period is critical for some crops and pastures, being already a reality in Mexico, Northeastern Brazil, Southern and Western Africa and India, where there is high exposure to CC conditions (Ericksen et al., 2011). This can be related to the rainfall variability in the tropical region, which is *ca.* 21% higher than average, with negative impacts on agriculture.

Impacts at the agricultural level – worldwide important crops

In order to adapt to CC it is crucial to clearly evaluate the effects on yield, taking into account that different factors and their interactions may indicate different adaptation strategies. While a rise in air [CO_2] can promote plant growth associated to higher C-assimilation rates, it may also increase plant canopy temperature related to a concomitant reduction of stomatal opening (Zhao et al., 2017), although in some crops (*e.g.*, coffee), the stomatal conductance was found to be mostly insensitive to rising [CO_2] (Ramalho et al., 2013, Rodrigues et al., 2016). On the other hand, changes in rainfall pattern can have an effect on crops, but projections on altered precipitation are uncertain (Zhao et al., 2017), and can be mitigated through irrigation. Still, in some cases the increase in air [CO_2] can also reduce (or cancel) the impact of drought on the photosynthetic performance (Avila et al., 2020). Several studies with climate models point out to temperature increase, as one of the most direct and wide negative impact on crops (Sultan and Gaetani, 2016; Porter and Gawith, 1999; Ottman et al., 2012), particularly if adaptation measures are not implemented by farmers (Zhao et al., 2017). Still, plants respond differently to temperature throughout their life cycles, that is, sensitivity/tolerance is also related to the phenological stage. Each species has a range of maximum and minimum values within which growth occurs. At optimum temperatures the progression of phenological phases is accelerated. At supra-optimal temperatures plant growth would progressively decrease, ceasing when a maximum is reached (Hatfield et al., 2011).

Beside the direct impacts of supra-optimal temperatures on production, important indirect effects are also involved. In fact, rising atmospheric temperature will increase the vapor pressure difference between leaf and atmosphere, leading to loss of water by transpiration and reducing water available in the soil (Zhao et al., 2017). In addition, shorter phenological phases will lead to shorter life-cycles, decrease in plant growth, lower radiation interception during growth, a shorter reproductive phase and a reduction in productive potential (Hatfield et al., 2011). Other indirect impacts include reduction on pollinating insects, and increase of weed species, pest and disease incidence (Ghini et al., 2011; Zhao et al., 2017). The effects of CC on agricultural productivity and livelihoods will intensify over the years with differences between countries or even between regions within each country. Such impacts will greatly depend on the actual local climate, how climate will locally changes, and other conditions of each place such as market access and soil conditions (Mendelsohn, 2009). Immediate action to increase agriculture sustainability, must be undertaken, to mitigate the negative impacts on crops, livestock, forests and fisheries, before they become widespread after 2030, with urban and mainly rural poor populations being exposed to highly volatile food prices (FAO, 2016). This will provoke food insecurity and promote poverty, especially through higher food prices and reduction of agricultural production, with an estimated increase in poverty of 35-122 million people in 2030, mainly due to CC negative impacts on the agricultural sector, especially in many countries that already shows serious food insecurity problems (Rozenberg and Hallegatte, 2015).

Food and agriculture must be a focus point to CC adaptation efforts, through policies and actions taking into account climate variability and market dynamics. This will reduce the sector's vulnerabilities and risks by promoting more sustainable, productive and resilient agricultural systems. To enhance effectiveness, science must adapt by reviewing research needs that can support decision-making (Howden et al., 2007).

However, the agricultural sector (and food production as a whole) also has major responsibilities in CC mitigation. Overall, agriculture, forestry and land-use change account for 20-24% of global GHG emissions (Smith et al., 2014). CO_2 emissions from agriculture are mainly related with losses of organic matter in the soil, changes in land use (*e.g.*, conversion of forests to pasture or cropland) and land degradation. Enteric fermentation in livestock, paddy rice production in flooded conditions, nitrogen fertilizers and manure contribute to CH_4 and N_2O emissions, which can be reduced through improved management practices (FAO, 2016). The share of GHG emissions from the agro-food sector is even higher when considering the emissions due to manufacture of agrochemicals and use of fossil fuel energy along the agricultural supply chain, as well as the emissions associated with agriculture's role in deforestation (Dickie et al., 2014), the latter case with profound environmental and socio-economic impacts worldwide (Reboredo, 2013; Reboredo and Pais, 2014).

It is estimated that wheat, rice, maize, and soybean provide about 2/3 of global human caloric intake (Zhao et al., 2017). Cereals represent 58% of the area harvested annually, using 215, 166 and 152 million hectares for wheat, rice, maize, respectively (Dawe et al., 2010), supplying directly *ca.* 50% of the world's food calories (Fischer et al., 2014). The fourth crop is soybean, which contributes to human caloric intake by being incorporated into animal feeds of high protein value and producing refined soybean oil (Fischer et al., 2014).

During the last century increase of 1 ºC in mean annual temperature in areas of wheat, rice, maize and soybean was observed. This rise is expected to continue during the present century, with yield losses relevant to the various climatic scenarios (Zhao et al., 2017). Therefore, the expected strong increase in world population will demand an assessment of the impact of global temperature rise on cereal production, and to improve cereal productivity while maintaining its overall supply (Powell et al., 2012), namely by screening and breeding more resilient cultivars (Scotti-Campos et al., 2014). This justifies a more detailed approach to these crops with regard to the likely impacts of CC, although many of the issues raised are common to other cultures.

Rice

Rice is the dominant human food crop, and is grown worldwide, but the Asia continent (from Pakistan in the West to Japan in the East) dominate consumption and *ca*. 90% of the world production (Dawe et al., 2010). Additionally, due to its wide consumption, including in developing countries, is being used to fulfill populations needs regarding some crucial micronutrients (*e.g.*, selenium and zinc) to human health, through biofortification practices (Lidon et al., 2018; Mangueze et al., 2018).

Without considering the increase in air CO_2 (C-fertilization), adaptation and genetic improvement measures, the rice production may be reduced by 3.2% for each increased ºC, although in some regions (such as India) larger temperature impacts, up to 6%, are expected (Zhao et al., 2017). However, considering that grain development and yield is maximal at the optimum temperature around 25 ºC, for each ºC above this temperature grain yield estimated to suffer a reduction of 10% until 35-36 ºC when yield become negligible (Hatfield et al., 2011). On the other hand, in some regions such as in China, a reduction in cold conditions will grant better conditions for irrigated rice production (Wang et al., 2016). Additionally, yield is significantly affected by spikelet sterility caused by extreme temperatures (above 33-35 °C), decreasing grain formation and size, shortening the growth duration and increasing maintenance respiration (Wassmann et al., 2010; Hatfield et al., 2011). Additionally, an increase in daily temperature during the grain filling stage affects some quality parameters such as opacity, amylose content and cooking quality (Uprety and Reddy, 2016). Drought impacts on this crop have not been adequately studied (Pandey et al., 2007) taking into account the predicted changes in rainfall patterns in the various CC scenarios (Bates et al., 2008). Floods may result in plants submergence, which is gradually becoming a main production constraint that affects *ca*. 15-20 million ha of rice fields in South and Southeast Asia (Redfern et al., 2012). Salinity problems are aggravated by high temperatures since transpiration demands lead to higher salt accumulation. This salt and heat stresses interaction is particularly relevant in the arid/semiarid regions, where plants have high water transpiration losses. Additionally, salinity will increase in coastal and delta regions affected by the rise in sea-levels (Wassmann et al., 2010).

Wheat

Wheat is a staple food for *ca*. 35% of the worldwide population (Scotti-Campos et al., 2014). Global wheat yield is expected to be reduced by 6% for each ºC increase in the global mean temperature (Sultana et al., 2009; Asseng et al., 2015; Zhao et al., 2017). In India, which accounts for 15% of world's wheat production, if air temperature will increase 0.8 ºC over the next 50 years, 51% of the actual area with high potential for wheat cultivation should be reclassified as heat-stressed (Hatfield et al., 2011). Temperatures above 25-35 ºC will reduce the grain filling period, and above 36 ºC and 14 ºC for diurnal and nocturnal periods, respectively, the floral rate will be reduced, with negative impact on grain yields (Hatfield et al., 2011). Reduced water availability will exacerbate these effects (Hussain et al., 2018). Simultaneous exposure to high [CO_2] and supra-optimal temperatures increases liquid photosynthesis (30 to 50%) and yield (15 to 30%), but only up to an increase of 2.6 ºC in the mean seasonal temperature. However, other studies reported yield losses of 29%, which decreased to only 25% considering the simultaneous increase in air CO_2 levels (Anwar et al., 2007). Additionally, although an increase in CO_2 levels doesn't affect grinding yield, the quality of the flour can be affected (Redden et al., 2014).

Maize

Meteorological data records show that mean annual temperatures have increased by *ca*. 1 ºC during the last century, and are expected to continue to further rise in the wheat, rice, soybean and maize cropping areas. Among the four major crops, maize is estimated to be the most affected with a global yield reduction between ca. and 20% for each ºC (Zhao et al., 2017; Rose et al., 2016). In the case of spring maize in Northeast China, CC led to a decline of the potential maize yield by an average of *ca*. 13% (Zhao et al., 2015). In some regions appropriate mitigation/adaptation measures (anticipating sowing or shifting cultivar) can reverse the impact of 1-2 ºC increase (Redden et al., 2014), although they will not prevent significant yield loss in tropical regions (Sultan and Gaetani, 2016). In response to temperature increases it was observed that maize reduced the duration of the reproductive phase, and of the life cycle. In addition, pollen viability and cell division in the grain endosperm decreases above 35 ºC and 30 ºC respectively (Hatfield et al., 2011).

Soybean

Even considering the possible fertilizer effect of increased air [CO_2], each ºC increase in global mean temperature would reduce soybean global yields by 3.1% (on average), although with a stronger impact of 6.8% in the United States (Zhao et al., 2017). However, with the addition of adaptation strategies, such as early planting or change of cultivars, no yield losses are expected where temperature increase is less than 2 °C and water was not limited (Rose et al., 2016). The highest grain yield, seed size, and harvest index of soybean is achieved at 23-24 °C, being progressively reduced as temperature rises above this optimum range, until no yield is observed at 39 ºC. Soybean exposure to high temperatures during the pollination stage have negative effects on the pollen growth and viability, with declines in pollen production (34%), pollen germination (56%) and pollen tube elongation (33%), leading to a reduced yield (Hatfield et al., 2011).

MEASURES FOR MITIGATION AND ADAPTATION OF AGRICULTURE

To address CC negative impacts, mitigation and adaptation are complementary approaches to significantly reduce agricultural systems vulnerability and food insecurity (Richardson et al., 2018). According to IPCC (2014) mitigation of CC can be defined as human interventions to reduce the sources or enhance the sinks of GHG, as well as reduce the sources of other substances which may contribute directly or indirectly to limiting CC. Adaptation reflects the ability to adjust to potential damage, allowing gradual and natural adjustment of ecosystems, ensuring food production and promoting sustainable economic development (Ericksen et al., 2011; IPCC, 2014). In fact, without the implementation of adaptation strategies against CC, it will not be possible to achieve food security, and eradicate hunger, malnutrition and poverty worldwide (FAO, 2016).

As regards Agriculture, Forestry and Other Land Use (AFOLU), mitigation actions can limit the magnitude or rate of long-term CC (IPCC, 2014). Apart of demand-side measures like reducing food-chain losses and wastes, changes in human diet, or changes in wood consumption, the main mitigation options involve one or more of three strategies (Smith et al., 2014):

1) Prevent emissions to the atmosphere by maintaining existing carbon pools in soils or vegetation or by reducing emissions of CH_4 and N_2O;
2) Increase carbon pools size by sequestration of CO_2 from the atmosphere;
3) Substitute fossil fuels by low-carbon energy sources.

It will be necessary to reduce CH_4 and N_2O emissions from livestock, animal manure, croplands and grazing lands, and to enhance C-sequestration through reduction deforestation and increasing afforestation and reforestation, as well as re-wetting drained peatlands and switching from tillage to no-till cropping. Other measures includes to reduce energy demand by increasing energy efficiency (simultaneously with the increased use of biofuels) to avoid the use of pesticides, fungicides and fertilizer use to reduce N_2O losses, to promote the use of plants with symbiotic capacity to capture atmospheric nitrogen and integration of different system components, such as agriculture, animal production and forestry, which is beneficial to the sustainability of farms (Smith et al., 2014).

In what regards biofuels the constraints to its development, mainly derived from agricultural and forestry wastes, are still in the horizon and the third generation of biofuels from micro and macro algae's, through hydrothermal liquefaction, is probably the best approach (Reboredo et al., 2016; Reboredo et al., 2017).

As regards adaptation measures (autonomous or planned), they can be undertaken with the existing technology, involving the development of new technologies or through institutional/market and policy reforms (Hertel and Lobell, 2014). Adaptation strategies can be tuned to the actual production system to offset the CC impacts. Increasing sowing density, changing sowing dates and covering soil with stubble, as well as the use of new technologies for water rainfall capture and storage, can potentially cancel or even enhance grain yield under future environmental conditions (Hertel and Lobell, 2014; Hussain et al., 2018). Furthermore, the selection and breeding of resilient plant varieties, with more adapted root (and shoot) architecture, with genes that confer resistance to drought and high temperatures will be determinant (Hertel and Lobell, 2014; Hussain et al., 2018). The planned adaptation includes funding and insurance (Botzen et al., 2009) and access to meteorological forecasts (Roudier, 2016). Implementation of such strategies depends on technology, institutions, wealth, equity, infrastructures and information/knowledge available (IPCC, 2015). Soil fertility can be restored with both high- and low-tech solutions, creating conditions to increase productivity, as well as climate variability resilience (Rosegrant et al., 2014). Solutions can range from new traits in varieties and water saving-irrigation technologies to practices for more efficient and sustainable use of resources. These technologies are in different stages of development and implementation across the world, and can include no-till, integrated soil fertility management, precision agriculture, organic agriculture, nitrogen-use efficiency, rainwater retention systems, drip or (micro-) sprinkler irrigation, improved tolerant cultivars (to heat and/or drought) and crop protection (Rosegrant et al., 2014). Implementation of such sustainable agricultural practices can lead to significant improvements in food security and resilience to CC. Just as an example, it is estimated that the number of people at risk of malnutrition in developing countries by 2050 may be reduced by over 120 million just due to the use of cultivars with greater nitrogen-use efficiency (FAO, 2016).

CONCLUSIONS

Agriculture is already being affected by CC with impacts unevenly distributed across the world. In fact, positive impacts can occur at higher latitudes in the future, but dramatic impacts on the tropical region will be unavoidable. In addition, should be considered the potential impacts on a wide range of sectors, including available water resources, floods in coastal areas and rivers, agriculture, environment, public health, construction, etc. Given the importance of the expected impacts of CC on agriculture (mainly from rising temperatures and water restrictions), and therefore on animal and human food, proper evaluation in this sector will be of paramount importance for anticipating the implementation of mitigation and adaptation, considering cultures of global (but also regional) importance. In this context, additional efforts are clearly needed to better quantify the uncertainties generated by CC, to increase knowledge regarding crop responsiveness and to implement mitigation and adaptation strategies that ensure the future of mankind.

Author contributions

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Conflicts of interest

The authors declare no conflicts of interest.

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