Nature Conservation 44: 117–139 (2021)
doi: 10.3897/natureconservation.44.64296
https://natureconservation.pensoft.net

REVIEW ARTICLE

A peer-reviewed open-access journal
Nature Conservation
Launched to accelerate biodiversity conservation

Economic effects of climate change on global agricultural production

Dániel Fróna[1,2], János Szenderák[1], Mónika Harangi-Rákos[1]

1 *Institute of Rural Development and Tourism Management, University of Debrecen, Böszörményi str. 138, 4032 Debrecen, Hungary* **2** *Karoly Ihrig Doctoral School of Management and Business, University of Debrecen, Böszörményi str. 138, 4032 Debrecen, Hungary*

Corresponding author: Dániel Fróna (frona.daniel@econ.unideb.hu)

Academic editor: Davy McCracken | Received 11 February 2021 | Accepted 30 June 2021 | Published 2 September 2021

http://zoobank.org/6EBCBF58-A7D2-4685-89A8-39BEC28D2A33

Citation: Fróna D, Szenderák J, Harangi-Rákos M (2021) Economic effects of climate change on global agricultural production. Nature Conservation 44: 117–139. https://doi.org/10.3897/natureconservation.44.64296

Abstract

Climate change seems to be larger, more complex and more unpredictable than any other environmental problem. This review deals with the economic effects of climate change on global agricultural production. The causes and consequences of climate change are very diverse, while populations in low-income countries are increasingly exposed to its negative effects. Supplying the population with food is possible with increased agricultural production, but this often occurs under unsustainable circumstances. Increased agricultural production is also one of the main sources of greenhouse gas emissions. In this research we highlight some of the important connections between climate change, population growth and agricultural production.

Keywords

Agriculture, climate change, food security, global challenges

Introduction

Currently, the combination of the rapidly changing economic environment, unbridled competition for natural resources, and the economic crisis have posed several challenges for agricultural and food companies. The growth of competition and the dynamically changing external environment are becoming increasingly difficult to deal with. The ability to respond in a timely manner to changing environmental impacts and regulations is essential. Agriculture is arguably one of the sectors which is most damaged by climate change. The food industry and the agricultural sector make a significant contribution to climate change, but are also particularly vulnerable to its effects. Technological progress aims to mitigate climate change effects and this makes it more important than ever to recruit, retain and train skilled employees (Kőmíves and Dajnoki 2016; Kőmíves et al. 2019). According to the definition of the Food and Agriculture Organization (FAO), food security is stable when all people have physical and economic access to sufficient, safe and nutritious food, which meets their dietary needs and preferences (WHO 2018). Extremes of climate change are expected to adversely affect the four pillars of food security – availability, access, utilization and stability – and their interactions. The long-term sustainability of the biosphere requires the rapid elimination of the overexploitation of non-renewable natural resources and the overexploitation of ecosystems induced by economic growth. Climate change affects food quantity (through direct effects on yields) and food quality, water availability and quality, the presence of pests, diseases and pollination. The available evidence indicates that climate change is already affecting food security and agriculture in a way that makes it more difficult to eradicate famine and starvation. Famine is especially serious in countries where agricultural systems are more sensitive to precipitation and sudden changes in temperature and where there is a high proportion of households with incomes strongly dependent on agriculture (Ripple et al. 2019). It is becoming increasingly difficult to sustainably feed humanity in adequate quantities and quality. These difficulties are partly due to human actions that have been carried out to date. The 150-year phase of rapid economic expansion and the resulting increase in greenhouse gas (GHG) emissions have globally raised temperatures by 1 °C on average, compared to the pre-industrial period. It is expected that with the current rate, the average global warming between 2030 and 2050 is likely to reach 1.5 °C. Climate models predict elevated average temperatures in most terrestrial and oceanic regions. Heavy rainfall and drought are increasingly likely to occur in the same area (Masson-Delmotte et al. 2018). These changes are increasingly affecting human systems and food production around the world. In South Asia and sub-Saharan Africa – currently areas with clusters of poverty and famine – agronomy is highly dependent on precipitation and is very sensitive to even small temperature changes. A large proportion of the population (up to 80% of rural households in some countries) are strongly dependent on agriculture. Populations whose living conditions are primarily based on agriculture are most at risk from hunger and food security issues caused by climate change. At the same time, climate change has far-reaching and multidimensional effects, where multiple areas are strongly connected. This research aims to review the different areas and their connections in terms of climate change impacts.

Methods

The overall aim of the article is to undertake a comprehensive review of the topic by processing the relevant international and scientific literature. Food security, climate change and subsistence security are interlinked at both global and national levels.

Qualitative research is suitable for exploring and synthesizing the results of previously conducted relevant research activities. The methodological examination of the data analysis process is often limited, while there are no systematic rules for the analysis of qualitative data. When raising research questions, authors need to consider the scope of keywords and topics that will be used to support early scoping exercises and subsequent literature reviews. Keywords provide a compact representation of the content of the document. In the case of this article the keywords were the following: climate change, agriculture, biodiversity, bio economy, water management, and their combinations. The economic impact of climate change on agricultural production was analyzed by processing the results of the relevant scientific literature. These research studies were mostly searched in the Google Scholar and databases and results were based on significant studies appearing between 2004 and 2021. The time period was selected to cover almost two decades and to ensure that the relevant research areas could be covered. At the same time, the latest databases of the Food and Agriculture Organization of the United Nations (FAO) were analyzed. We examined the trends between 1960 and 2018, where the data range was limited by data availability. Based on these data sources, the most important results were collected in order to achieve a comprehensive review of the effects. Graphical representations can help readers better interpret and understand the results. We used RStudio to visualize the data from the aforementioned databases. The program supports the graphical display of the analyzed data. Comparing results is difficult, because most results can be seen as a rough approximation of future development.

Results and discussion

Population, food security and hunger

Climate change is an increasing risk factor for the world's hungry and malnourished people because almost 822 million people are not fed satisfactorily (Sen 2019). In addition, over 2 billion people suffer from one or more micronutrient deficiencies, called hidden hunger (Fróna et al. 2019). The number of hungry people, which used to show a declining trend, has been rising again since 2015. The FAO has attributed this shift to constant insecurity in conflict-affected regions, economic slowdowns in calmer regions and destructive climate experiences (Conforti et al. 2018). For instance, the "El Niño" weather event of 2015–2016, aggravated by higher sea surface temperatures in addition to several other factors, is thus widely responsible for disrupting food security in many countries. Since the early 1990s, the amount of intense weather-related catastrophes has doubled, adversely affecting the productivity of major crops and contributing to rising food prices, which has also led to a loss of income (Sen 2019). These catastrophes have had a disproportionately negative impact on people living in poverty and further restricted their access to food. One of the most important gaps in climate change-related decision-making is the definition of climate change as a complex challenge – i.e. carbon emission privileges, carbon sequestration capacity and emission cuts – rather than consumption, economic growth and social choices (Pelling et al. 2015). Certainly, the threats caused by climate change can be traced back to production, consumption patterns and certain social behaviors. Only in current years has the debate on climate change been restructured to focus on consumption opportunities and people's lifestyles, equality of responsibility, and the so-called climate justice and consumption opportunities. This shift is an essential step towards building social harmony for the broad changes in the current economic value systems and consumption patterns, principally in high-income nations, to avoid the devastating consequences of a significantly warmer world, including an increase in hunger and malnutrition in the near future. The global population is still growing by about 80 million persons a year, more than 200 000 a day on average (Bongaarts and O'Neill 2018).

The side effects associated with population growth are among the primary drivers of global change. Therefore, it is essential to become familiar with the demographic developments that have taken place and are expected in the near future. Demographic booms were linked to the development of agricultural technologies. The development of agriculture is estimated to have started at about 10 000 BC, when the global population was about only 2.4 million people (Ourworldindata 2018). Between 1 and 100 AD, the population of the Earth was around 188 million. As an outcome of the Industrial Revolution, with the advances in medicine and health care, significant changes have taken place. By the late 1800s, worldwide population had reached and exceeded one billion people (Ourworldindata 2018). At the present time, 1.4 billion people live in China alone (UN 2017). In the 1930s, with the widespread use of maize hybrids, the overall population surpassed 2 billion. Around 1960 the global population reached 3 billion, which was partly related to the Green Revolution. The global population grew to 6 billion in the 20th century (Worldometers 2019). Figure 1 shows global population growth based on the FAO database for the period from 1950 to 2018. In the analyzed period alone, population had nearly quadrupled by 2018. Based on current growth trends, a further increase can be expected but at a slower pace, since the growth rate of the global population has fallen from the 2.2% experienced 50 years ago to today's 1.05%. Currently, nearly 7.8 billion people live on Earth, according to the Worldometers (2021).

The differences were important, since the populations of Africa and Asia are considerably greater than in Europe or in Americas.

The changes in food consumption cannot be explained by population growth itself. It is beyond debate that the amount of food consumed is clearly influenced by the size of the population, while the quality of the food consumed depends on the average income of households (Fróna et al. 2019). Indirectly, changing household incomes will increase the amount of food consumed, since consumers usually start to restructure their diet when income increases. Figure 2 shows the global population growth by region. The figure shows that the Asian region achieved a more than threefold increase from 1951 to 2018, while clear growth can also be seen in the African region. Simultaneously, there is a clear decrease in the European region with an almost stagnant growth rate.

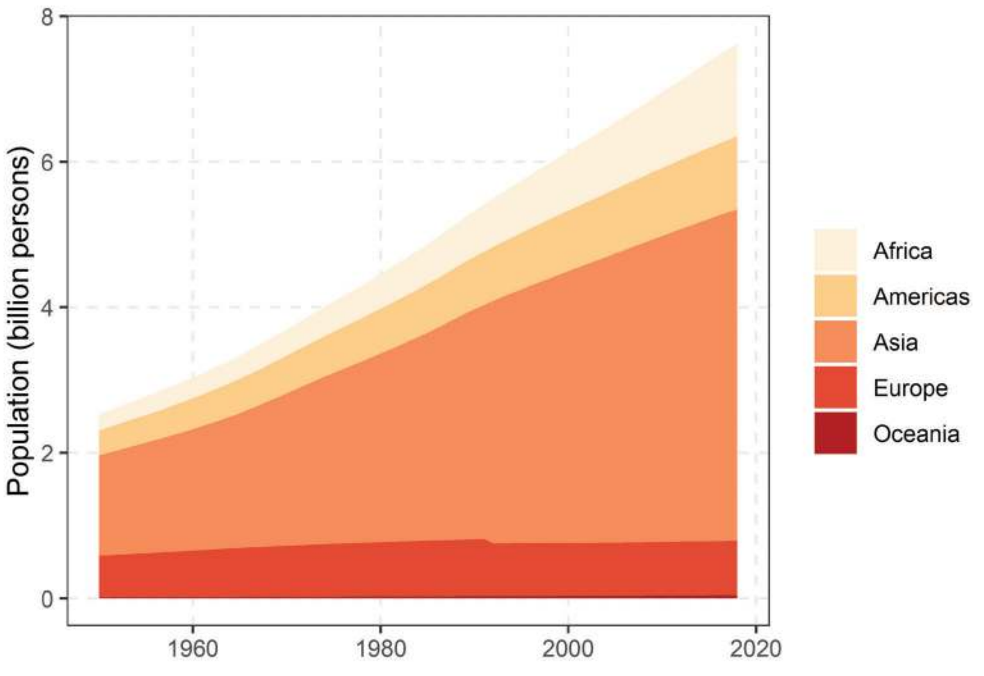

Figure 1. The increasing global population between 1950 and 2018. Source: authors' own editing, based on the database of FAOSTAT, 2020 (FAO 2020a). Globally, population was three times more in 2018 than it was in 1950 (an increase from 2.5 billion to 7.6 billion). In Asia, the growth exceeded the global increase (3.3 times more in 2018 compared to 1950), while in Africa, the growth was more than fivefold compared to 1950. The population growth in the same period was only 1.3 times more in Europe and 2.9 times more in the Americas.

Land use and land management

The harmful causes of climate change also contribute to soil degradation. Degradation can also be attributed to direct and indirect anthropogenic activities. Figure 3 shows the change in the global agricultural area and that of the European Union based on the FAO database, between 1971 and 2016.

Approximately 10% of the global surface is covered by glaciers, another 19% is comprised of barren land – deserts and dry salt areas. More than a half of the habitable land is used by agriculture. Another 37% is covered by forest, and 11% is bush and grasslands. The remaining 1% is the built environment, i.e. urban areas, which include towns, villages, highways, roads and other human infrastructure. Land use is unequally distributed between animals and plants intended for human consumption. Land (with pasture) for the produce of animal feed is responsible for 77% of global agricultural land (Ritchie and Roser 2020). Land use change and land management have an immense effect on the ecosystem and biodiversity. Hong et. al. (2021) analyzed the global drivers of land use emissions between 1961 and 2017. They estimated the net cumulative emissions to be 657 Gt CO_2-eq, which averaged out at 11.5 Gt annually.

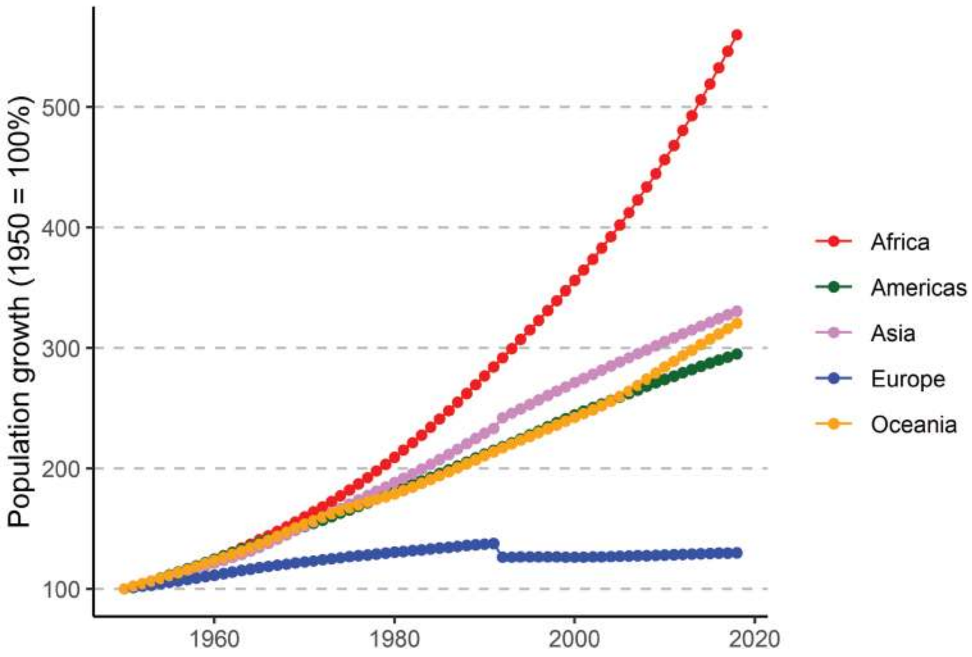

Figure 2. Population growth by regions between 1950 and 2018. Source: authors' own editing based on the database of FAOSTAT (FAO 2020a). Compared to 1950, the largest growth rates were recorded in the developing regions, mainly Africa and Asia. In developed regions, especially in Europe, a stagnating population is expected. These differences have great consequences. The large population increase and its regional differences will further exacerbate the issues related to the food system, which could increase food insecurity problems.

The 2017 value (14.6 Gt) was 24% greater than in 1961, reflecting an overall increase in emissions from the intensification of agriculture. Latin America, Southeast Asia and sub-Saharan Africa were the major emitting regions (accounting for more than two-thirds of global emissions growth in the analyzed period). The large increase in land use emissions in these regions was associated with cropland expansion and the emission intensity of land use. At the same time, mostly beef and a few other red meats provided only 1% of calories globally, but accounted for 25% of all land use emissions (Hong et al. 2021).

Climate change and climatic extremes might greatly affect the food chain, from the production process to consumption. Factors caused by humankind, including global food production, increase the average global temperature by 0.2 °C per decade (Masson-Delmotte et al. 2018). The number of extreme weather events such as storms, fires, floods and droughts has increased globally (Woodward et al. 2014). There has been a rise in the global mean sea level (GMSL), which is around 19 centimeters higher on average than it was in 1900 (EEA 2021). All manifestations of climate change have a direct and an indirect negative impact on food security, food production, and thus on the availability, accessibility and quality of food.

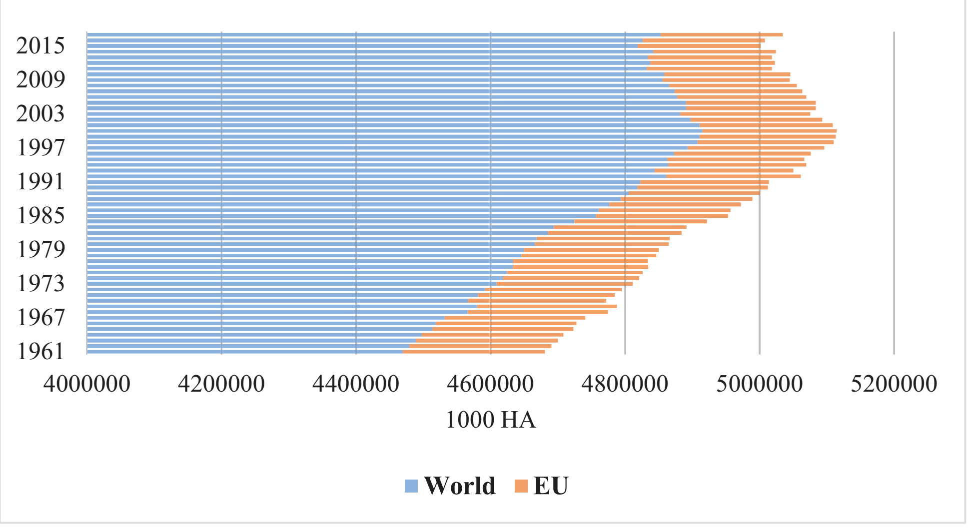

Figure 3. Global agricultural land use change between 1961 and 2017. Source: authors' own editing based on the database of the FAO (FAO 2020c). Agricultural land is limited and further expansion can be hardly expected, since the creation of agricultural land is accompanied by deforestation and the destruction of natural habitats. At the same time, competition for agricultural land has increased significantly, especially with the appearance of biofuels. This has led to the food versus fuel debate in the past decades (Horton et al. 2019).

Climate and water issues

There is general agreement that the global warming tendencies of the last century are most likely due to human activities (Oreskes 2004; Doran and Zimmerman 2009; Anderegg et al. 2010; Cook et al. 2016). In addition, the main global scientific organizations have issued public statements in support of this opinion (FAO, IPCC, NASA etc.). Scientists are convinced that global temperatures will continue to rise during the coming decades, largely due to greenhouse gases produced by human activity. Figure 4 shows the change in mean temperature between 1961 and 2018. Observing the tendency, further increase can be expected, which is also well illustrated by the trend line drawn on the world average.

The water scarcity problem is one of the most urgent climate-related issues requiring a solution. Heffernan (2013) remarks that drought has been present throughout history and the situation could get worse in the near future, exacerbated by human-induced climate change (Heffernan 2013). The availability of freshwater resources shows a similar picture to the availability of land, i.e. it is globally more than sufficient, but its distribution is very unequal. Access to water resources also varies greatly: there are great varieties between countries in the same region, but even within a country, which can lead to alarming levels of water scarcity in some areas. This is common in countries in the Middle East, North Africa, and South Asia where land resources are insufficient. At present, there are still plenty of ways to enhance the effectiveness of water usage (for

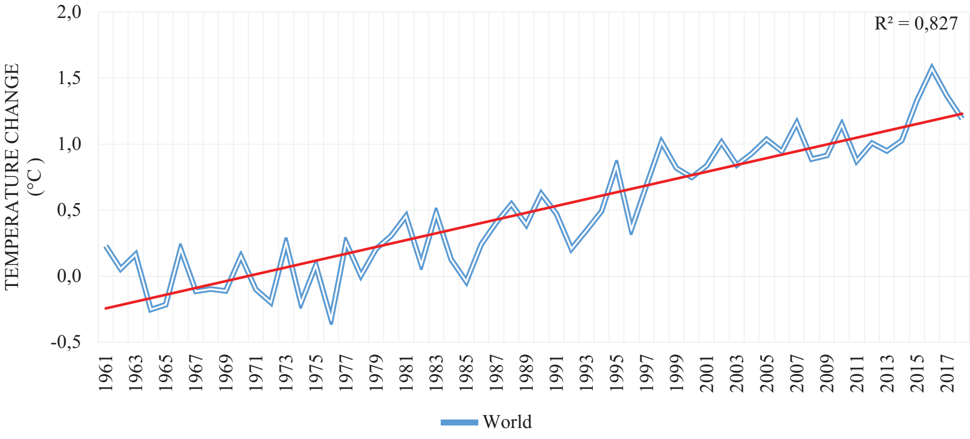

Figure 4. Global temperature change between 1961 and 2018. Source: authors' own editing based on the database of the FAO (FAO 2020c). Mean surface temperature change compared to the period 1951–1980. Temperature anomalies have increased in the past few decades, which has further intensified global concerns and led to further debates and action.

example, by providing appropriate incentives to use less water) (EASAC 2017). This is because water demand is likely to be extended by 100% until 2050, which can also be determined by urbanization, population growth and the impacts of climate change. As a result of urbanization, domestic and industrial water use is expected to double. Climate change entails the possibility of more extreme weather events, which can be accompanied by a doubling of water use in crop production (Fróna et al. 2019).

Water critically influences plant productivity and food production, and is an essential factor in food production processes, while it also plays an important part in food security. Changes in water demand, availability and quality caused by climate change will influence water management outcomes. Adjustment measures needed to ensure adequate water management require both supply-side and demand-side strategies. Nevertheless, the water requirements of crop production have increased due to the spread of irrigated agriculture (Bates et al. 2008). The most important climatic factors for water availability are temperature, precipitation, and evaporation demand (determined by the characteristics of the soil, wind speed, atmospheric humidity and temperature). Changes in water demand and water availability because of climate change are likely to modify the water flow of rivers, which will have a significant impact on water availability (Bates et al. 2008). Future directions will be significantly affected by increasing urbanization. Rising living standards, changing consumption preferences and growing demand for goods all require more water (Rembold et al. 2019). According to Molden et. al. (2010) there is a considerable scope for improving water productivity, but the possibilities for different regions and different systems are unequal. Sub-Saharan Africa and South Asia are the regions with the highest potential gains. These areas are among the poorest regions globally, thus increasing water productivity could help to reduce poverty and improve agricultural outcomes at the same time. However, these developments have usually been slowed down since producers have not prioritized the improvement of water gains (Molden et al. 2010).

As the result of higher temperature, water scarcity, higher atmospheric carbon concentrations and extreme events such as heat waves, droughts and floods, food production is likely to decrease. Weather disturbances and climate change might affect food prices and thus access to food (Ripple et al. 2019). Yields of vital food crops are already shrinking due to increasing extreme events, the unstable water supply and different plant diseases. At least 80% of the century-old changes in cereal production in semiarid regions can be attributed to climate variability (Conforti et al. 2018). Because of the high number of interconnections among global food systems, an extreme event occurring in one part of the food chain can cause a problem in another region which can have a potential impact on the entire global food system. While many crucial food production areas have felt the impact of climate factors on yields, rising food prices have been partly offset by a combination of national policy responses (WHO 2018). Poor regions and countries are more interested in their food security and adaptation to climate change. Particular attention should be paid to the fact that low-income countries and vulnerable people are not able to adapt so easily when a sudden shock occurs (Fellmann et al. 2018). Climate change is increasingly affecting water resources used in food production. Currently, 1.8 billion people live in areas that are exposed to the risk of insufficient water supply, which is nearly a quarter of the global population. According to projections, this phenomena will affect half of the entire population by 2030 (Woodward et al. 2014). Climate-linked catastrophes, such as heat waves, floods, droughts, and storms, account for 80% of all internationally reported disasters. During the period between 2011 and 2016, much of the world was hit by a severe drought that led to a crisis involving the food security of 124 million people in 51 countries (Masson-Delmotte et al. 2018).

Energy utilization

Energy consumption and utilization are critical points of climate change research, especially the food – energy – water nexus. Rasul and Sharma (2016) emphasized the importance of a system-wide and holistic approach in designing effective adaptation policies and strategies. Sectoral approaches may overlook important aspects of the food – energy – water nexus and the impact of climate change. The connection between the energy and the agricultural sectors has been further strengthened by the increasing role of biofuels. Biofuels are made from agricultural input materials, and as Rasul and Sharma (2016) noted, this has made biofuels vulnerable to the impact of changes in climate variables (Rasul and Sharma 2016).

Figure 5 shows the levels of energy consumption in global agriculture, expressed in thousand terajoules. The overall energy consumption in agriculture has increased considerably since 1970. There has been a considerable growth in the gas-diesel oil and electricity consumption. Around 1970, the agricultural consumption of gas-diesel oil was around 834 thousand terajoules, while it was 247 thousand terajoules in the case

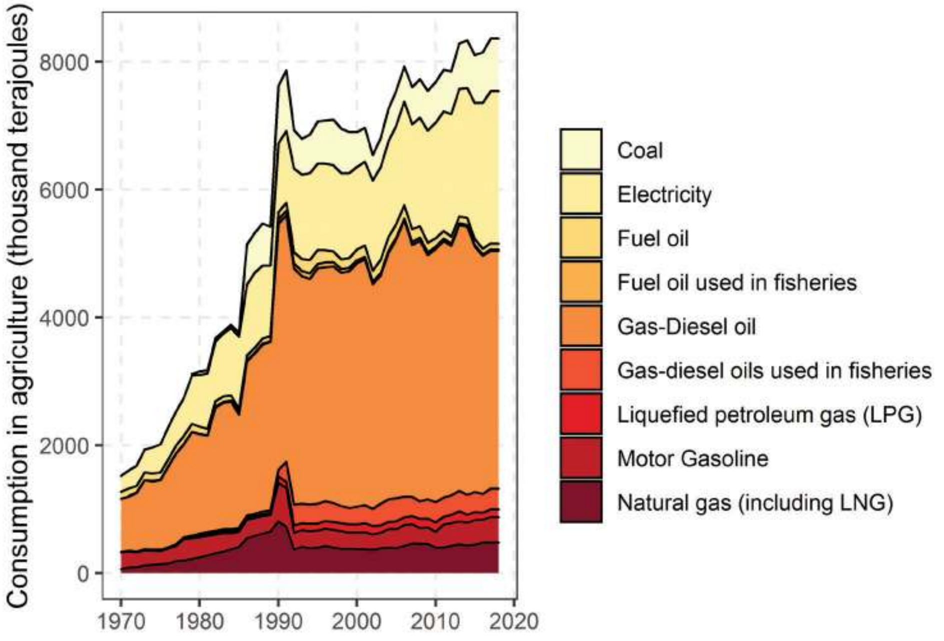

Figure 5. Global energy consumption in agriculture between 1970 and 2012. Source: authors' own editing based on the database of the FAO (FAO 2020c). Intensive agricultural and food systems have led to a boost in energy consumption globally. Gas-diesel oil consumption in agriculture has increased 4.4 times compared to 1970, while growth in electricity consumption has exceeded the 1970 level by 9.6 times. In some cases, an extreme growth in consumption has been recorded. For example, coal consumption was more than 34 times higher in 2018 compared to 1979 (an increase from 23 thousand terajoules to 824 thousand terajoules).

of electricity. These numbers have increased to 3722 thousand terajoules and 2385 thousand terajoules, respectively. This implies that the gas-diesel oil consumption in agriculture has increased almost fivefold and electricity consumption has increased almost tenfold. The large growth in consumption indicates the increase in agricultural production. It is worth emphasizing that while the actual crude oil and natural gas resources are not affected by climate change, access to them and our knowledge of them could be affected (for example diminishing ice cover in the Arctic region may improve access possibilities). At the same time, the increase in extreme weather events could restrict access to the oil and gas supply (Rasul and Sharma 2016).

Energy consumption and greenhouse gas emissions are closely connected. Changes in energy consumption are mostly affected by carbon dioxide emissions in different regions globally. Based on the results, reductions in GHG emissions and energy consumption would require much stronger policy initiatives than those so far discussed by policy makers. The reason behind this is that energy conservation policies are expected to slow down the current stage of economic growth (Khan et al. 2014). The transition from a fossil fuel-dependent to a bio-based economy is a challenging problem, as presented in the comprehensive review by Popp et. al. (2021). As they note, biomass

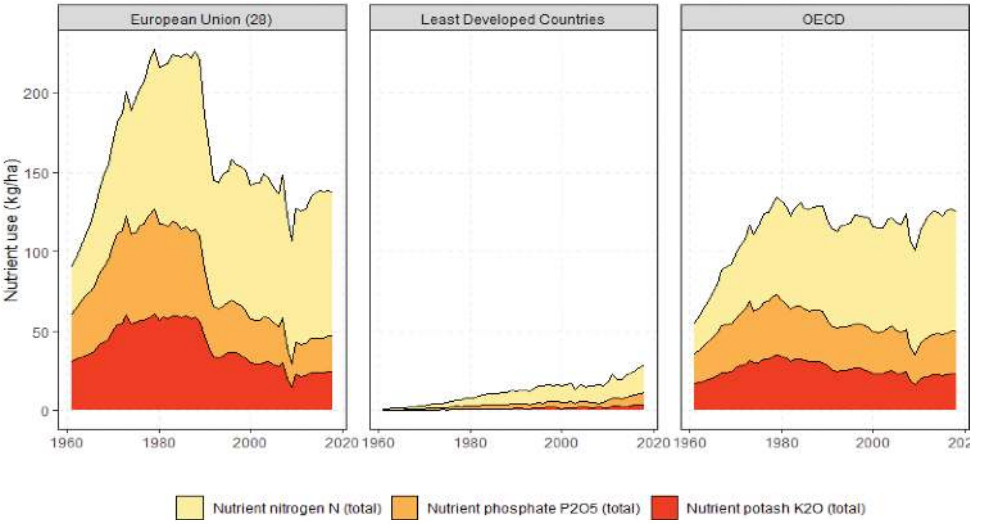

Figure 6. Fertilizer use in the EU, OECD and in the least developed countries between 1961 and 2017. Source: authors' own editing based on the database of the FAO (FAO 2020c). Fertilizer use per area of cropland largely increased until the 1980s. Generally, in the most developed regions, decreasing fertilizer use could be recorded, while a further reduction can be expected in the future due to environmental concerns.

demand is expected to increase with the transition to a low-carbon economy. However, biomass has a limited availability and food security has priority over all other uses. Still, it has an important role in energy production as it reduces both dependency on fossil fuels and GHG emissions. Crop production residues could contribute considerably in this respect (Popp et al. 2021).

Figure 6 shows the nitrogen, phosphate (P2O5) and potash (K2O) nutrient use in the OECD (Organization for Economic Co-operation and Development) countries, in the EU and in the less economically developed countries between 1961 and 2018. The use of global nitrogen fertilizers has quadrupled since 1961 in the OECD countries, although nitrogen use has been stagnating since 1980. There has been a three-fold increase in the EU as well, but there has also been a slight decline in the past few decades due to increased efficiency and sustainability. The same tendencies have occurred wi th phosphate and potash use per area of cropland. Fertilizer use in the least developed countries has increased from 0.77 kg/ha in 1961 to 17.61 kg/ha in 2018 on average. This amount is almost 23 times more than the base amount in 1961. The growth is even more extreme in the case of phosphate (43 times more) and potash (29 times more). Despite this, the levels of use per cropland area are much less in the least developed countries compared to the OECD countries. For example, the average nitrogen use was 75 kg/ha in the OECD in 2018, while it was only 17 kg/ha in the least developed countries.

Nitrogen fertilizer increases the mineralization of soil organic matter, resulting in a reduction in the natural organic matter stock. This has led to a great deal of controversy in achieving long-term sustainability. In some parts of the planet, enormous and uncontrolled synthetic N-fertilization has had a damaging effect on the environment (Mahal et al. 2019). Excessive nitrogen use is a serious source of danger for already scarce freshwater supplies. The many areas under water management that sustain and provide food for the expanding human population have come under stress. Rivers, lakes and underground water layers dry out or become too polluted for use (Lane et al. 2017). Agriculture accounts for a massive proportion of water consumption – more than in any other sector –, and there is also the problem of inefficiently utilized water. Agriculture uses 70% of the fresh water available to the world, of which approximately 60% is wasted by wasteful, leaking irrigation systems, and inefficient application methods and crop cultivation (Romero-Lankao et al. 2017). Many top agriculture producer countries, including the United States of America, China, and India, have reached or are very close to reaching their water resource limitations. The problem is exacerbated by the fact that agriculture also generates considerable freshwater pollution through pesticides and fertilizers, which affect the lives of humans and other species (Trimmer and Guest 2018).

Potential effects on biodiversity

The expansion of agriculture has led to one of the greatest adverse effects on habitat, changing the environment and exerting further pressures on biodiversity. The IUCN (International Union for Conservation of Nature) Red List estimated that 28 000 species are threatened with extinction, while agriculture alone is responsible for the extinction of 24 000 species. However, it is also known that these effects can be reduced, either through dietary changes, by replacing some meat consumption with plant-based alternatives, or through innovations in technology (Ritchie and Roser 2020).

Although biodiversity is essential to agriculture and human well-being, it is declining at an unprecedented rate (FAO 2020b; Pereira et al. 2012). Agriculture, especially livestock, and biodiversity have a special connection, since as the FAO (2020b) notes, “depending on the ecological context and land use history, livestock is either among the most harmful threats to biodiversity or necessary to maintain high nature value farmland”.

Biodiversity and its related areas can be analyzed only in a broad context. Oliver and Morecroft (2014) analyzed the climate change and land use interactions on biodiversity. According to their results, biodiversity was impacted through a wide range of interactions of climate change and land use (Oliver and Morecroft 2014). Suitable adaptation and conservation strategies are necessary to reduce the negative impact of climate change, which take the interactions and possible feedbacks into account. Henle et al. (2008) reviewed the conflicts between biodiversity conservation and agricultural activities in agricultural landscapes. The major reasons behind the biodiversity-related conflicts were the intensification of agriculture, the abandonment of marginally productive but high nature value (HNV) farmland, and the changing scale of agricultural operations (Henle et al. 2008). The factors mentioned by Henle et al. (2008) are still relevant to satisfy the growing food demand, although the Common Agricultural Policy

(CAP) has an increasing focus on environmental issues. Pereira et al. (2012) remarked, that biodiversity change is mostly driven by habitat change and overexploitation, but the role of pollution, exotic species and diseases were also important factors. Climate change can be regarded as an emerging driver of biodiversity change. As a response to climate change, species are shifting their ranges and the extinction risk of species has already increased at high northern latitudes. In these regions, it can be expected that birds and plants will be most affected by further climate impacts.

In most cases, scientific research focuses on the negative effects of climate change, but Bellard, Bertelsmeier, Leadley, Thuiller, and Courchamp (2012) noted that climate change could also have positive effects on biodiversity (Bellard et al. 2012). Many plants could benefit from the more clement temperatures and increased CO2 in terms of biomass production. Milder winters and increased precipitation may benefit threatened species as well. Biodiversity is often positively affected by intermediate levels of disturbance. For example, extensive and low-input livestock systems can be of high natural value (FAO 2020b). Lomba et al. (2020) noted that farmlands could provide a diverse cultural and natural heritage globally if managed under low-input farming systems (Lomba et al. 2020). At the same time, inappropriate management practices, such as overgrazing in low-input systems or nutrient pollution in high-input intensive systems, could occur and have negative impacts on biodiversity (FAO 2020b). Furthermore, as Pereira et al. (2012) remarked, not all biodiversity change is negative, since it should be assessed in a broader context with its consequences for ecosystem services and species existence values (Pereira et al. 2012).

A major issue is that we do not know yet how mitigation of greenhouse gas emissions could reduce biodiversity impacts. Climate change is expected to have a large effect at every system level. Warren et al. (2013) analyzed the changes in the future climatic ranges of common and widespread species globally (Warren et al. 2013). According to their estimates, without mitigation, almost 60% of plants and ~35% of animals are expected to lose more than 50% of their present climatic range by the 2080s. With mitigation, losses are expected to be reduced by 40–60%, depending on the emission peak. At the same time, according to Pereira et al. (2012), species were reported to be negatively affected by climate change in regions that were not suffering a great deal of warming (mainly the Cape region and southeastern Australia).

Climate change affects areas which have a great importance, not only in biodiversity conservation, but in providing a wide range of socioeconomic services. According to Lomba et al. (2020), high nature value (HNV) farmlands are of great importance in Europe, because they cover a high proportion of Europe's agricultural land, support biodiversity conservation and offer a wide range of ecosystem services. These farmlands and the associated farming systems were adapted to the natural conditions where they have been implemented. The preservation of these areas is important since they contribute to agricultural production, and biodiversity conservation and provide a wide range of ecosystem services. Although many of these farmlands are under pressure from climate related challenges, the two major threats to these areas are agricultural intensification and farmland abandonment. Lomba et al. (2020) list the alternative future scenarios for HNV farmlands, which include the "Business-as-usual HNV farmlands", "Museum landscapes", "Back-to-nature", "Production farmlands" and "Viable HNV farmlands" scenarios. Depending on the possible future directions, some of these scenarios could contribute to the mitigation of climate change. For example, the "Back-to-nature" scenario assumes that halting HNV farmland loss fails to become a long-term societal priority. In this scenario, replacement of farmlands by forest ecosystems could provide regulating ecosystem services, especially climate change mitigation tools. At the same time, legal options and the trade-off between rewilding and farmland abandonment should be debated as well.

Due to its complexity, it is extremely hard to include biodiversity in environmental assessments in an effective way (FAO 2020b). Accurate prediction and effective solutions are still missing, despite the threat posed by climate change. Bellard et al. (2012) addressed several problems with model estimations, especially the under- or overestimation of risk for biodiversity. The diversity of approaches, methods, scales and assumptions had led to the lack of a coherent picture. These results were supported by Oliver and Morecroft (2014) in terms of climate change and land use interactions. Garcia, Cabeza, Rahbek, and Araújo (2014) argued that forecasting the long-term impacts of climate change on biodiversity is challenging, since species and community dynamics are very complex, in addition to the interaction with other stressors (Garcia et al. 2014). Also, due to the large number of undiscovered species, climate change assessment represents only a small portion of biodiversity. Lack of data on the majority of species is also a contributing factor. Urban et al. (2016) draw attention to the importance of developing accurate predictions about biological responses to climate change. The inclusion of several important biological mechanisms would increase the accuracy of predictions. Urban et al. (2016) also highlighted possible mechanisms and practices to help collect the detailed data necessary for modelling, while Henle et al. (2008) noted that sustainable conflict resolution strategies need to take into account the levels of conflicts and the differences in terms of geographical scale (Urban et al. 2016).

The use of scenario analyses comes from military planning, but it was also extended to the strategic planning of businesses and other organizations in the early 1960s, where policymakers systematically analyzed the long-term consequences of investments and other strategic decisions. The aim of working with different scenarios is not to foretell the future, but to better perceive the uncertainties in the continuously changing environment in order to make decisions that have a crucial effect on a wide range of potential future issues (Moss et al. 2010).

Complexities of climate change effects

Figure 7 shows a simple framework of the causes and effects of anthropogenic activities connected to climate change. The WHO has comprehensive estimations of the diseases and mortality caused by anthropogenic climate change by 2030, following projections from the global climate model concerning GHG emission scenarios. Studies claiming a correlation between health and climate have highlighted the estimation of relative

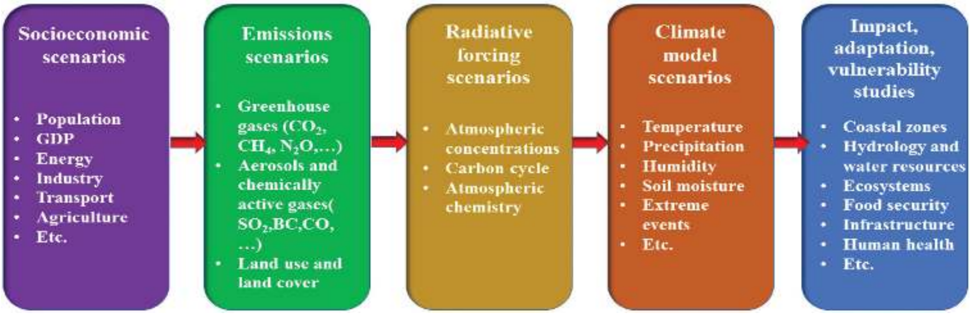

Figure 7. A sequential approach to climate change. Source: authors' own construction based on Moss et.al (2010).

changes in climate-sensitive health outcomes, including cardiovascular disease, malaria, diarrhea and various forms of malnutrition. This is only an incomplete list of possible health issues, while serious uncertainties occur in all underlying models. Therefore, these estimates should be taken into account as moderate, evaluated estimates of the health strains of climate change. Nevertheless, the total deaths caused by climate change were estimated to be at least 150 000 people per year by 2000 (Patz et al. 2005).

Climatic scenarios describe possible future climatic circumstances. They are used to help assess the impacts of climate change and the options of adaptation, while providing information to decision-makers (Fróna 2020). However, climate scenarios can involve several fluctuations, such as the often mentioned elements of climate, such as temperature, precipitation, cloud cover, humidity and wind. They might project the above factors as an annual or seasonal average and in a daily or even shorter resolution (Parson et al. 2007; Moss et al. 2010). Adjunct scenarios change the present conditions by plausible but arbitrary amounts. For example, the temperature of a region may increase by 2, 3, or 4 °C under current conditions, or may increase or decrease by 5, 10, or 20%. Such adaptations may be performed on annual or seasonal averages, for long periods of current conditions, or for temperature/precipitation variability over days, months, or years. Similarly to the simple emission scenarios used to compare climate models, adjunct climate scenarios are easy to prepare, but they do not represent currently valid future states. They are carried out for original exploration studies of climate effects and for testing the sensitivity of collision models (Parson et al. 2007). By using climate models, the current climate and its responses to past disruptions are studied, and scenarios for future climate change are compiled under specific scenarios of emissions and other disruptions. Just as modelling future climate change requires the determination of future emission trends, assessing the future effects of climate change requires the determination of future changes in the climate. Data from a climate change scenario can be used to assess the impact of freshwater systems, agriculture, forests, or any other climate-sensitive system or activity. Impact assessments can use a variety of methods, including quantitative models such as hydrological and yield models, threshold analyses which examine the qualitative disturbances in the behavior of climate-sensitive systems, or expert opinions integrating a variety of scientific knowledge (Parson et al. 2007).

The results of the several consistent models show the strong negative effects of climate change, especially in regions where developing countries are concentrated. Simulations that take into account specific nitrogen stress outcomes have significantly more severe consequences of climate change and have an impact on adaptation planning (Rosenzweig et al. 2014). A number of forecasting systems are available for climate extremes and food security. These systems make it possible to study the effects of climate extremes on agriculture and food security.

Some of the tools available:

- ASAP – (Anomaly Hotspots of Agricultural Production)
- ASIS – (Agriculture Stress Index System)
- GEOGLAM CM4EW – (Global Agricultural Monitoring) (European Commission 2019).
- General Circulation Model (GCM) projections.

Other plants or food sources that are vitally important for humanity might be affected by climate change. The greater proportion of research deals with the four main field crops – wheat, rice, maize and soybeans – in the case of negative climate change impacts, despite the fact that many other crops are essential for achieving food security and healthy nutrition. Climate issues cause modifications in agriculture; therefore temperature and water resources affect livestock farming as well. FAO studies claim that the most harmful event related to climate change is drought (Masson-Delmotte et al. 2018).

A changing climate might exacerbate losses within the global food system. About a third of the food produced by farmers is lost between production and the market in low- and middle-income countries. The proportion in high-income countries is almost the same, with a similar percentage being wasted at different points of the food chain (Gustavsson et al. 2011). The present food system accounts for 21–37% of total net human emissions. This will further exaggerate climate change and its impacts without providing a better food security system (Arneth et al. 2019). In fact, in addition to placing a huge stress on insufficient environmental resources, this level of food loss is a factor in maintaining food insecurity. Climate change can significantly affect food security and agriculture, although the impacts might vary across different regions. To ensure the future food demand and security of the growing population, there is a crucial need for agriculture to adapt to the negative impacts of a changing climate. The diverse adaptation strategies may include changing land and crop production practices, changing food consumption and waste management techniques and the development of improved plant varieties (Anderson et al. 2020). Climate-intelligent agriculture might promote synergies between productivity, adaptation and mitigation, although the spread of these technologies could be strongly restricted (Loboguerrero et al. 2019).

The production, transport and consumption of food reaches far beyond the production areas of farmers (and producer countries). Therefore, the food system approach offers a better opportunity for analysis. The food systems approach offers significant advances in terms of adapting to and mitigating climate change. By explicitly acknowledging the fundamental links between consumer demand, dietary change and production, it supports the much broader integration of actors and institutions. However, the intensification of climate responses requires further research (Rosenzweig et al. 2014). Consuming primarily plant-based foods could enhance human health and significantly reduce greenhouse gas emissions by reducing the global consumption of animal products. In addition, the area needed to produce animal feed would be freed up and plants necessary for human food could be grown in its place. It is necessary to drastically reduce the large amount of food wastage globally (Ripple et al. 2019). Managing food waste is of paramount importance in guaranteeing food security (Corrado et al. 2019). It is a challenge to find an appropriate balance and tradeoff between food waste/lost and food security. Solutions that seem credible often increase consumer risk. In order to meet both aspects, there is a need for cooperation and development among actors within the food chain (both consumers and authorities) (Kasza et al. 2019). Teaching about sustainable development needs to be integrated into educational programs, offering a variety of subjects with more comprehensive guidelines. The fight against hunger would be more effective with new and inclusive institutional teaching frameworks, which could enable and promote more social action (Sánchez García et al. 2019).

Conclusion

Climate change is affecting developing countries in particular, where urbanization, growing water scarcity and a lack of technological development remain the most crucial challenges to be dealt with. Technology and knowledge transfer have so far provided only limited assistance to developing countries. By formulating efficient adaptation strategies, the negative effects of climate change on food security can be mitigated or even avoided. Within the food system, adaptation activities are aimed at reducing vulnerability and enhancing the flexibility of the system to climate change. In a few regions, extended climate events are changing agro-ecological zones. Adaptation to extreme experiences is intended to minimize damage, modify hazards and avoid damaging effects or share losses, thereby creating a more flexible system. In addition to current and expected climate change, adaptation requires both technological (new varieties produced by biotechnology or breeding) and non-technological (e.g. land management, markets, food change) solutions.

Without a collective approach, climate change effects cannot be mitigated sufficiently. Even with the tremendous efforts made at present, several areas are lagging behind. However, several future directions have been clearly outlined in the research literature. With increasing populations, growing demand and changing diets are expected in the future. These demands can only be satisfied with further productivity gains, since agricultural land expansion is extremely limited. Meat consumption, especially beef and other red meats, should be limited within reasonable limits. This is a viable, but difficult task, since currently meat substitutes are not widely accepted among consumers and large-scale production is still a problem (Cole et al. 2018; Good Food Institute 2021). Raising awareness of products and increasing trust should be a priority in this area. At the same time, the consumption imbalance between developed and developing countries has to be mitigated as well. We have to add that a reduction in meat consumption should be discussed in the context of marginalized lands and biodiversity. Furthermore, alternative diets with lower meat consumption have clear health benefits (Tilman and Clark 2014), which should be taken into account as well.

By reducing the current levels of food loss and food waste, several emission "gaps" between the current and the expected levels of emissions can be reduced. This would require a complex strategy along the whole food value chain. Furthermore, food loss and waste solutions should be linked to existing problems, such as plastic waste pollution, since the food industry is one of the major users of plastics. Finally, one of the most urgent problems is water scarcity. Since water supply distribution is very unequal globally, innovative solutions are needed in agriculture to achieve further productivity gains. By implementing precision agriculture methods, the whole production process can be monitored and controlled. Finally, data collection, transparency and interdisciplinary approaches will gain further importance in the future as well.

In terms of biodiversity connections, achieving socioeconomic viability and preserving the cultural and natural heritage of HNV landscapes are of great importance, although climate change inherently affects these regions. At the same time, it is hard to quantify these effects and their possible future directions without suitable data and assessment methods. Evaluating these effects would require an even more complex approach with highly detailed data. Existing models should be extended to include different social and economic interactions, as well. According to the FAO (2020b), an effective knowledge transfer strategy, and cultural awareness and appreciation have been major success factors in maintaining and improving biodiversity.

The solution to these problems also depends on collective and interdisciplinary efforts and cooperation between public authorities and the scientific community. Adaption to climate change and to its negative effects causes a significant transformation in the interaction between global society and the natural ecosystem. Government agencies have issued several climate emergency statements. In addition to policy makers, cooperation between the private sector and the public needs to be established to overcome the harmful impacts of climate change.

Acknowledgements

Supported by the ÚNKP-20-3-II New National Excellence Program of the Ministry for Innovation and Technology from the resources of the National Research, Development and Innovation Fund. University of Debrecen, Károly Ihrig Doctoral School of Management and Business.

References

Anderegg WR, Prall JW, Harold J, Schneider SH (2010) Expert credibility in climate change. Proceedings of the National Academy of Sciences of the United States of America 107(27): 12107–12109. https://doi.org/10.1073/pnas.1003187107

Anderson R, Bayer PE, Edwards D (2020) Climate change and the need for agricultural adaptation. Current Opinion in Plant Biology 56: 197–202. https://doi.org/10.1016/j.pbi.2019.12.006

Arneth A, Barbosa H, Benton T, Calvin K, Calvo E, Connors S, Cowie A, Davin E, Denton F, van Diemen R (2019) IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Technical report, Intergovernmental Panel on Climate Change.

Bates B, Kundzewicz Z, Wu S (2008) Climate change and water. Intergovernmental Panel on Climate Change Secretariat, Geneva, 214 pp. https://doi.org/10.1017/CBO9780511546013

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecology Letters 15(4): 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Bongaarts J, O'Neill BC (2018) Global warming policy: Is population left out in the cold? Science 361(6403): 650–652. https://doi.org/10.1126/science.aat8680

Cole MB, Augustin MA, Robertson MJ, Manners JM (2018) The science of food security. npj Science of Food 2: e14. [8 pp.] https://doi.org/10.1038/s41538-018-0021-9

Conforti P, Ahmed S, Markova G (2018) Impact of disasters and crises on agriculture and food security, 2017. Food and Agriculture Organization of the United Nations, Rome, 168 pp.

Cook J, Oreskes N, Doran PT, Anderegg WR, Verheggen B, Maibach EW, Carlton JS, Lewandowsky S, Skuce AG, Green SA, Nuccitelli D, Jacobs P, Richardson M, Winkler B, Painting R, Rice K (2016) Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. Environmental Research Letters 11(4): e048002. https://doi.org/10.1088/1748-9326/11/4/048002

Corrado S, Caldeira C, Eriksson M, Hanssen OJ, Hauser H-E, van Holsteijn F, Liu G, Östergren K, Parry A, Secondi L, Stenmarck Å, Sala S (2019) Food waste accounting methodologies: Challenges, opportunities, and further advancements. Global Food Security 20: 93–100. https://doi.org/10.1016/j.gfs.2019.01.002

Doran PT, Zimmerman MK (2009) Examining the scientific consensus on climate change. Eos, Transactions – American Geophysical Union 90(3): 22–23. https://doi.org/10.1029/2009EO030002

EASAC (2017) Opportunities and challenges for research on food and nutrition security and agriculture in Europe. EASAC policy report 34. European Academies Science Advisory Council. German National Academy of Sciences Leopoldina, 80 pp.

EEA (2021) Global and European sea level rise. European Environment Agency. Prod-ID: IND-193-en. https://www.eea.europa.eu/data-and-maps/indicators/sea-level-rise-7/assessment [accessed: 14.06.2021]

European Commission (2019) Tools on Climate extremes and food security. Knowledge Centre for Global Food and Nutrition Security. European Commission. https://ec.europa.eu/knowledge4policy/global-food-nutrition-security/tools-climate-extremes-food-security_en

FAO (2020a) Annual population. FAOSTAT. Food and Agriculture Organization (FAO). http://www.fao.org/faostat/en/#data/OA

FAO (2020b) Biodiversity and the livestock sector – Guidelines for quantitative assessment. Version 1. Food and Agriculture Organization of the United Nations. Rome, 2020. Livestock Environmental Assessment and Performance Partnership (FAO LEAP). https://doi.org/10.4060/ca9295en

FAO (2020c) Database. FAOSTAT. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/faostat/en/#data

Fellmann T, Witzke P, Weiss F, Van Doorslaer B, Drabik D, Huck I, Salputra G, Jansson T, Leip A (2018) Major challenges of integrating agriculture into climate change mitigation policy frameworks. Mitigation and Adaptation Strategies for Global Change 23(3): 451–468. https://doi.org/10.1007/s11027-017-9743-2

Fróna D (2020) Factors affecting food security. The Annals of the University of Oradea. Economic Sciences XXIX(1): 39–49.

Fróna D, Szenderák J, Harangi-Rákos M (2019) The Challenge of Feeding the World. Sustainability 11(20): e5816. https://doi.org/10.3390/su11205816

Garcia RA, Cabeza M, Rahbek C, Araújo MB (2014) Multiple dimensions of climate change and their implications for biodiversity. Science 344(6183): 1–10. https://doi.org/10.1126/science.1247579

Good Food Institute (2021) The science of cultivated meat. https://gfi.org/science/the-science-of-cultivated-meat/ [accessed: 02.04.2021]

Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A (2011) Global food losses and food waste. Extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome, 38 pp.

Heffernan O (2013) The dry facts. Nature 501(7468): S2–S3. https://doi.org/10.1038/501S2a

Henle K, Alard D, Clitherow J, Cobb P, Firbank L, Kull T, McCracken D, Moritz RF, Niemelä J, Rebane M, Wascher D, Watt A, Young J (2008) Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe – A review Agriculture. Ecosystems & Environment 124(1–2): 60–71. https://doi.org/10.1016/j.agee.2007.09.005

Hong C, Burney JA, Pongratz J, Nabel JE, Mueller ND, Jackson RB, Davis SJ (2021) Global and regional drivers of land-use emissions in 1961–2017. Nature 589: 554–561. https://doi.org/10.1038/s41586-020-03138-y

Horton P, Bruce R, Reynolds C, Milligan G (2019) Food Chain Inefficiency (FCI): accounting conversion efficiencies across entire food supply chains to re-define food loss and waste. Frontiers in Sustainable Food Systems 3(79): 1–11. https://doi.org/10.3389/fsufs.2019.00079

Kasza G, Szabó-Bódi B, Lakner Z, Izsó T (2019) Balancing the desire to decrease food waste with requirements of food safety. Trends in Food Science & Technology 84: 74–76. https://doi.org/10.1016/j.tifs.2018.07.019

Khan MA, Khan MZ, Zaman K, Naz L (2014) Global estimates of energy consumption and greenhouse gas emissions. Renewable & Sustainable Energy Reviews 29: 336–344. https://doi.org/10.1016/j.rser.2013.08.091

Kőmíves PM, Dajnoki K (2016) Labour market integration issues related to migrants arriving to Hungary. Annals of the University of Oradea Economic Science 25: 363–373.

Kőmíves PM, Pilishegyi P, Novák N, Nagy AS, Körösparti P (2019) The Role of the Higher Education in the Development of the Agriculture. International Journal of Information and Education Technology 9(9): 607–612. https://doi.org/10.18178/ijiet.2019.9.9.1275

Lane A, Norton M, Ryan S (2017) Water Resources: A New Water Architecture. John Wiley & Sons, 328 pp. https://doi.org/10.1002/9781118793985

Loboguerrero AM, Campbell BM, Cooper PJ, Hansen JW, Rosenstock T, Wollenberg E (2019) Food and earth systems: Priorities for climate change adaptation and mitigation for agriculture and food systems. Sustainability 11(5): e1372. https://doi.org/10.3390/su11051372

Lomba A, Moreira F, Klimek S, Jongman RH, Sullivan C, Moran J, Poux X, Honrado JP, Pinto-Correia T, Plieninger T, McCracken DI (2020) Back to the future: Rethinking socioecological systems underlying high nature value farmlands. Frontiers in Ecology and the Environment 18(1): 36–42. https://doi.org/10.1002/fee.2116

Mahal NK, Osterholz WR, Miguez FE, Poffenbarger HJ, Sawyer JE, Olk DC, Archontoulis SV, Castellano MJ (2019) Nitrogen fertilizer suppresses mineralization of soil organic matter in maize agroecosystems. Frontiers in Ecology and Evolution 7: e59. https://doi.org/10.3389/fevo.2019.00059

Masson-Delmotte V, Zhai P, Pörtner H, Roberts D, Skea J, Shukla P, Pirani A, Moufouma-Okia W, Péan C, Pidcock R (2018) IPCC, 2018: Summary for Policymakers. Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, 32 pp.

Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J (2010) Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management 97(4): 528–535. https://doi.org/10.1016/j.agwat.2009.03.023

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282): 747–756. https://doi.org/10.1038/nature08823

Oliver TH, Morecroft MD (2014) Interactions between climate change and land use change on biodiversity: Attribution problems, risks, and opportunities. Wiley Interdisciplinary Reviews: Climate Change 5(3): 317–335. https://doi.org/10.1002/wcc.271

Oreskes N (2004) The scientific consensus on climate change. Science 306(5702): 1686–1686. https://doi.org/10.1126/science.1103618

Ourworldindata (2018) World Population over the last 12,000 years and UN projection until 2100. https://ourworldindata.org/world-population-growth

Parson EA, Burkett V, Fisher-Vanden K, Keith D, Mearns L, Pitcher H, Rosenzweig C, Webster M (2007) Global-change scenarios: their development and use. Synthesis and Assessment Products. US Department of Energy Publications, Washington DC, 118 pp.

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. Nature 438(7066): 310–317. https://doi.org/10.1038/nature04188

Pelling M, O'Brien K, Matyas D (2015) Adaptation and transformation. Climatic Change 133(1): 113–127. https://doi.org/10.1007/s10584-014-1303-0

Pereira H, Navarro L, Martins I (2012) Global Biodiversity Change: The Bad, the Good, and the Unknown. Annual Review of Environment and Resources 37(1): 25–50. https://doi.org/10.1146/annurev-environ-042911-093511

Popp J, Kovács S, Oláh J, Divéki Z, Balázs E (2021) Bioeconomy: Biomass and biomass-based energy supply and demand. New Biotechnology 60: 76–84. https://doi.org/10.1016/j.nbt.2020.10.004

Rasul G, Sharma B (2016) The nexus approach to water–energy–food security: An option for adaptation to climate change. Climate Policy 16(6): 682–702. https://doi.org/10.1080/14693062.2015.1029865

Rembold F, Meroni M, Urbano F, Csak G, Kerdiles H, Perez-Hoyos A, Lemoine G, Leo O, Negre T (2019) ASAP: A new global early warning system to detect anomaly hot spots of agricultural production for food security analysis. Agricultural Systems 168: 247–257. https://doi.org/10.1016/j.agsy.2018.07.002

Ripple WJ, Wolf C, Newsome TM, Barnard P, Moomaw WR (2019) World Scientists' Warning of a Climate Emergency. Bioscience 70(1): 8–12. https://doi.org/10.1093/biosci/biz088

Ritchie H, Roser M (2020) Land Use Our World in Data. Our World in Data. https://ourworldindata.org/land-use

Romero-Lankao P, McPhearson T, Davidson DJ (2017) The food-energy-water nexus and urban complexity. Nature Climate Change 7(4): 233–235. https://doi.org/10.1038/nclimate3260

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh TAM, Schmid E, Stehfest E, Yang H, Jones JW (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences of the United States of America 111(9): 3268–3273. https://doi.org/10.1073/pnas.1222463110

Sánchez García JL, Beiro Pérez I, Díez Sanz JM (2019) Hunger and sustainability. Economic Research. Ekonomska Istrazivanja 32(1): 850–875. https://doi.org/10.1080/1331677X.2019.1583588

Sen A (2019) The political economy of hunger. Common Knowledge 25(1–3): 348–356. https://doi.org/10.1215/0961754X-7299462

Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515(7528): 518–522. https://doi.org/10.1038/nature13959

Trimmer JT, Guest JS (2018) Recirculation of human-derived nutrients from cities to agriculture across six continents. Nature Sustainability 1: 427–435. https://doi.org/10.1038/s41893-018-0118-9

UN (2017) World Population Prospects 2017. United Nations. Department of Economic and Social Affairs. Population Dynamics. https://population.un.org/wpp/DataQuery/

Urban MC, Bocedi G, Hendry AP, Mihoub J-B, Pe'er G, Singer A, Bridle J, Crozier L, De Meester L, Godsoe W (2016) Improving the forecast for biodiversity under climate change. Science 353(6304): 1–9. https://doi.org/10.1126/science.aad8466

Warren R, VanDerWal J, Price J, Welbergen JA, Atkinson I, Ramirez-Villegas J, Osborn TJ, Jarvis A, Shoo LP, Williams SE, Lowe J (2013) Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nature Climate Change 3(7): 678–682. https://doi.org/10.1038/nclimate1887

WHO (2018) The State of Food Security and Nutrition in the World 2018: Building climate resilience for food security and nutrition. Food and Agriculture Organization of the United Nations, Rome, 202 pp.

Woodward A, Smith KR, Campbell-Lendrum D, Chadee DD, Honda Y, Liu Q, Olwoch J, Revich B, Sauerborn R, Chafe Z, Confalonieri U, Haines A (2014) Climate change and health: On the latest IPCC report. Lancet 383(9924): 1185–1189. https://doi.org/10.1016/S0140-6736(14)60576-6

Worldometers (2019) Current world population. https://www.worldometers.info/world-population/ [retrieved: 2021.02.16]

Worldometers (2021) Current world population. https://www.worldometers.info/world-population/ [accessed: 01.05.2021]