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RESEARCH ARTICLE

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Review of climate change issues: A forcing function perspective in agricultural and energy innovation

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Summary

Climate change is observed globally, and the projections predict that the change will continue in the future for quite a long time. The mitigation and adaptation to climate change, however, are offering tremendous business opportunities around the world, especially for businesses operating in the agri-food, energy, finance, and health sectors, water infrastructure, built environments, and other relevant services. When the severity of heat waves is considered, for instance, it would become quite clear that the demand for cooling would accelerate, putting further stress on energy supply and increasing the risk of electricity black outs. Similarly, the projections also provide warnings about increased drought risk in many regions around the globe, and even worse, it should also be emphasized that 60% more food will be needed globally, while 100% more demand for food is projected in developing countries by the year 2050. While all these are being projected, we are experiencing progressively increasing stress on our global freshwater resources, which are worsened further by climate change-driven impacts and water pollution. Consequently, reducing agri-food production systems' susceptibility to climate change and strengthening the resilience of such systems are extremely important to sustain and improve the livelihoods of billions of people around the globe. Moreover, reducing emissions due to fossil fuels consumption and production is vital for the whole global population, and agri-food and energy sectors have tremendous potentials for reducing inefficiencies and emissions while simultaneously playing their crucial roles in food and energy security as well as poverty reduction. Both of these sectors are facing significant climate change-driven challenges, which provide ample opportunities for cutting-edge novel knowledge and innovative products, processes, services, and policies. And due to the reciprocal relationships between climate change and agri-food and energy innovations, in return, complementing the other forms, such innovations will speed up the climate change mitigation and adaptation processes.

KEYWORDS

climate change, energy, greenhouse gas emissions, innovation, agri-food

1 | INTRODUCTION

Climate change is observed globally. Both land and sea temperatures are increasing while at the same time precipitation patterns are changing, and the frequency and intensity of climatic extremes are increasing around the globe. Key sectors such as agriculture, energy, fishing, tourism, and water supply as well as others will have to adopt new and innovative approaches and solutions for mitigating and adapting climate change, in order to have resource security and sustainable economic development in the future.[1] Different climate projections predict that the change will continue in the future for quite a long time and that climatic extremes will be more often and more severe. Every passing day, businesses and governments are realizing that they have to plan and build for resilience to climate change. And it is exactly these adaptation and mitigation measures that are offering tremendous opportunities, especially for businesses operating in the agri-food, energy, finance, and health sectors, water infrastructure, built environments, and other related services. When the severity of heat waves is considered, it becomes obvious that the demand for cooling would rise and accelerate, putting further stress on energy supply and increasing the risk of having more electricity black outs. Similarly, projections provide warnings about declining quality water availability and dangerously increased drought risks in many regions around the globe. Moreover, and even worse, the United Nations has emphasized that 60% more food will be needed globally, while 100% more demand for food is projected in developing countries by the year 2050.[2] Approximately 70% of freshwater resources are being used for agri-food production[3] and while all the above-mentioned projections are being predicted, we are experiencing a progressively increasing stress on our global freshwater resources, which are worsened further by climate change-driven impacts and water pollution.[4] Consequently, reducing the susceptibility of agri-food production systems to climate change and strengthening the resilience of such systems are extremely important to sustain and improve the livelihoods of billions of people around the globe. Furthermore, agri-food and energy sectors have tremendous potentials for reducing inefficiencies and emissions while simultaneously playing their crucial roles in food and energy security as well as in poverty reduction. In summary, it is crystal clear that both sectors are facing significant climate change-driven challenges, which at the same time provide tremendous opportunities for not only novel knowledge, products, and processes but also innovative services and policies. This article, rather than focusing on the changes or general impacts of changes in climatic variables on the environment (as usually the case), first highlights the impacts of major changes in climatic variables on the environment, agriculture, and energy sectors, and then providing specific cases, and pointing targets and potential opportunities, discusses the reciprocal relationships between climate change and agri-food and energy innovations as crucial societal responses to climate change for better managing our resources and improving our own environment.

2 | CLIMATE CHANGE AND POLICY FRAMEWORK

Climate is defined as the statistical averages, trends, magnitude, and variability of the climate system over 30+ years, while the climate system is described as a complex system that includes the atmosphere, hydrosphere, upper lithosphere, and biosphere and powered by the incoming solar (shortwave) radiation, which is in long-term balance with the outgoing terrestrial (longwave) radiation (Figure 1). The Earth's surface absorbs approximately 50% of the shortwave radiation, and the remaining is reflected back to space or absorbed within the atmosphere by different components. The energy absorbed warms the Earth's surface and is then emitted as terrestrial (longwave) radiation back to the atmosphere, where it is partially absorbed by different atmospheric components (eg, carbon dioxide [CO_2], other greenhouse gases [GHGs], clouds, and aerosols). These constituents also emit longwave radiation in all directions, and the component emitted downwards is partly trapped and adds heat to the lower atmosphere and the surface of the Earth, creating what is called the greenhouse effect. If the change in an identified climatic variable persists for more than a few decades or so, then this change is defined as a climate change[6], which can be caused by both natural and anthropogenic forcing functions, such as solar cycles and GHG emissions, respectively.

2.1 | Observed and projected changes in climate

Our activities, such as the increased GHG concentrations released by fossil fuel production and consumption, agricultural practices, land-use, and forest management practices are all affecting the climate. The current annual average of atmospheric CO_2 concentration is almost 400 ppm, which currently stands as the highest concentration observed over the past 800 000 years or so. And this concentration is approximately 40% higher than the levels observed in the preindustrial era of the mid-18th century (Figure 2). Roughly, the entire surface of the globe,

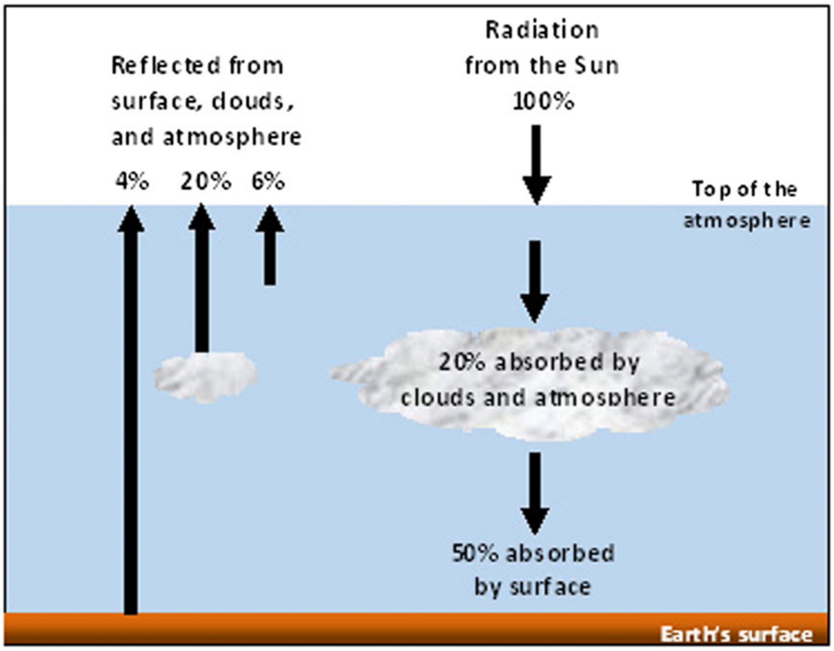

FIGURE 1 Schematic distribution of solar radiation after it falls on the Earth (modified after Taylor[5]) [Colour figure can be viewed at wileyonlinelibrary.com]

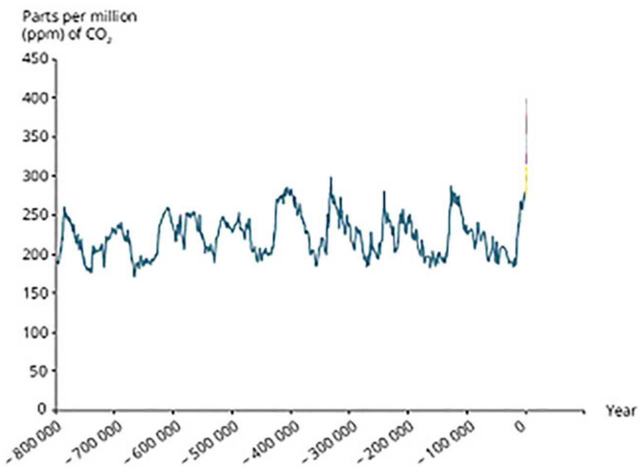

FIGURE 2 CO_2 concentration in the atmosphere[7] in the last 800 000 years [Colour figure can be viewed at wileyonlinelibrary.com]

although not evenly, has warmed up since the 1850s (Figure 3). Globally, the year 2015 was recorded as the warmest year[11], and the global average surface temperature was reported to be approximately 1°C higher than that of the preindustrial period. The Arctic ice, glaciers, and mountain snow covers have melted and are retreating rapidly due to the increased temperatures. For instance, in Europe, the reconstruction studies showed that the observed summer temperatures in recent decades are the warmest temperatures observed over the period of last 2000 years.[12] The strongest warming in Europe seems to be observed over southern Europe. Observations have also revealed increases in ocean heat content and therefore increase in sea level (Figure 4). The IPCC AR5 estimated that, during the period of 1901 to 2015, a total increase of approximately 19.5 cm in the global mean sea level (GMSL) was observed, and this is equivalent to 1.7 mm increase per year.[15] Changes in global precipitation since 1900 have demonstrated trends in both positive and negative directions.[6] We have enough observed evidence in many climatic variables, including extremes, which can be attributed to anthropogenic forcing functions.[16,17] It was also concluded by the IPCC AR5 that "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century."[15] Anthropogenic forcing functions have impacted the global water cycle in multiple directions as well, including increases in precipitation-related events.[18] Our past activities will continue to rule the climate for many more years to come because of the dynamics of the climate system and the life cycle of GHGs even if the anthropogenic GHG emissions were to fall to zero today. Climate change assessments are typically made by using the general circulation models (GCMs), and these models project that warming will be particularly strong at high latitudes. And increasing precipitation is projected for high latitudes and the equatorial Pacific, whereas decreasing precipitation is projected for many subtropical and midlatitude regions, including the Mediterranean region. For instance, northern Europe is predicted to become wetter, while the southern parts will become much drier in the 2080s particularly under the high emissions scenario (where total radiative forcing function was set to approach 8.5

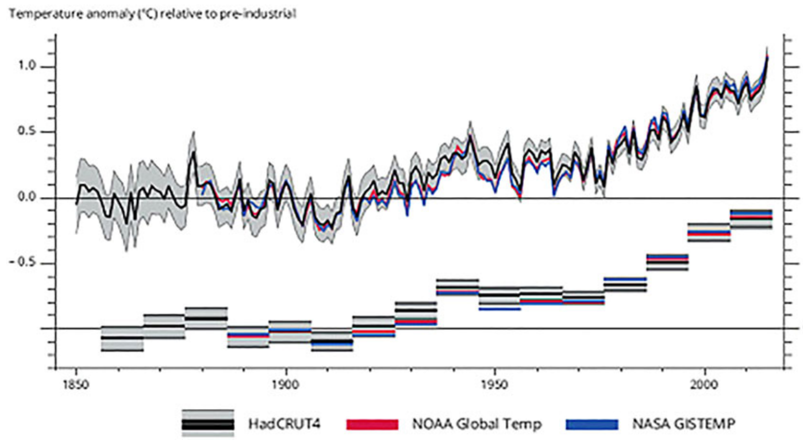

FIGURE 3 Global average near-surface temperatures between 1850 and 2015 relative to the preindustrial period (HadCRUT4,[8] NOAA Global Temp,[9] and GISTEMP[10]) [Colour figure can be viewed at wileyonlinelibrary.com]

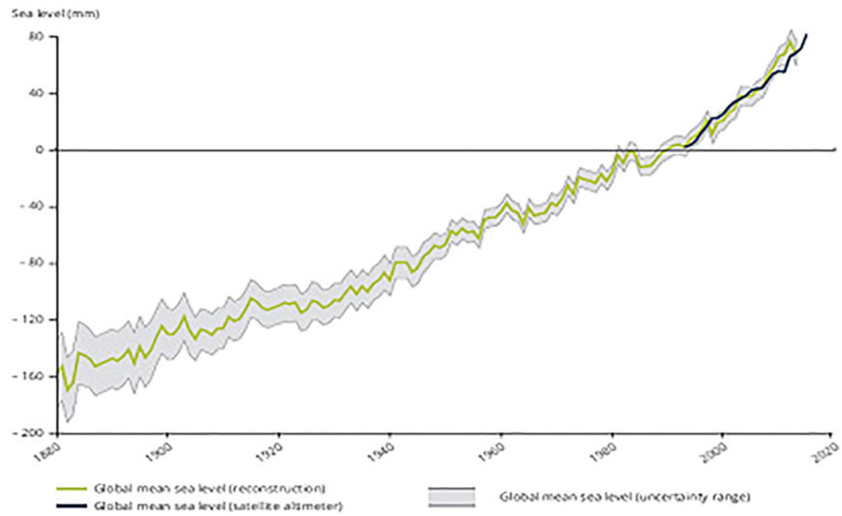

FIGURE 4 Observed change in global mean sea level[13,14] [Colour figure can be viewed at wileyonlinelibrary.com]

W/m^2 by the year 2100 and go beyond afterwards) (Figure 5). Globally speaking, mostly over land areas, the record-breaking temperatures are to be observed more often, and the severity and durations are to increase. Figure 6 shows the European situation under the abovementioned high emissions scenario, where very extreme heat events are predicted to be observed more often and even worse situations to be observed in southern and southeastern regions of Europe. Globally, we have observed more intense precipitations more often as well; however, significant differences were observed across regions, seasons, etc. As an example, Figure 7 shows the observed trends in heavy precipitation across Europe between the years of 1960 and 2015. Available projections also concur that the heavy precipitation event frequency and the total amount of precipitation from such events will intensify in the future in many parts of the globe.[6] Figure 8 demonstrates the projections in heavy precipitation events over the period of 2071 through 2100 compared with those of the period of 1971 to 2000 for the high emissions scenario.

2.2 | Global policy framework

The UNFCCC[23] addresses the global threat of climate change, and its goal is stated as to maintain GHG concentrations at an acceptable level so that human impacts on the climate system could be eliminated. And these concentrations have to be realized within a reasonable time frame, which would facilitate natural ecosystems to adapt themselves to the changes in climatic variables, so that global food security is not jeopardized and a sustainable development is maintained. In order to mitigate climate change, the Kyoto Protocol was eventually drafted and accepted in 1997, and legally bound the participating countries to achieve GHG emissions reduction targets by the declared first commitment period of 2008 to 2012.[24] In an effort to stop rising global temperature relative to those of the preindustrial era, within the framework of "Cancun agreements," the global community agreed to reduce the GHG emissions[25], and this necessitates the emissions to be cut by 40% to 70% compared with the 2010 figures by 2050.[26] And eventually, 197 countries

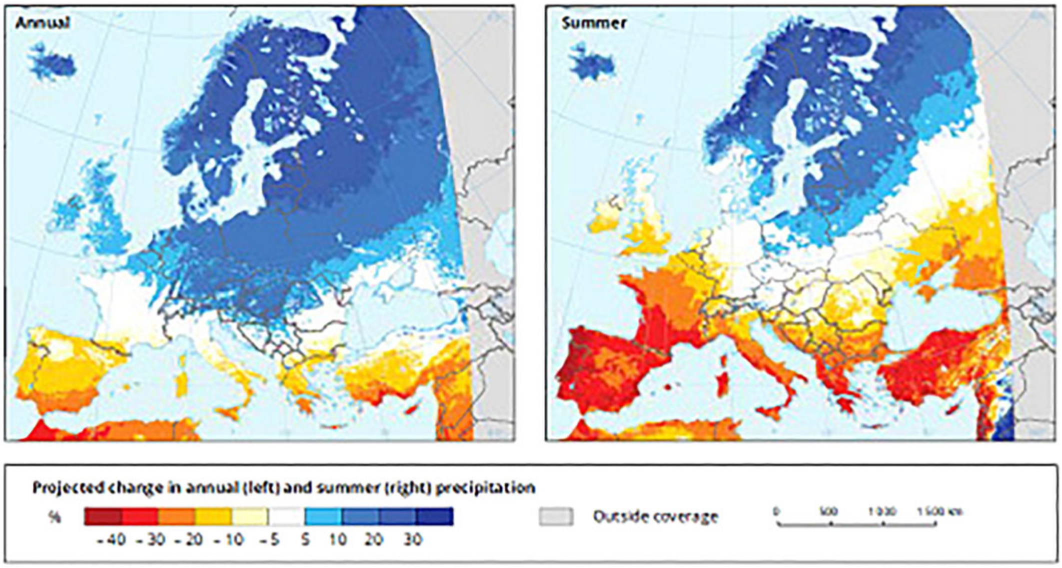

FIGURE 5 Projected changes in annual and summer precipitation across Europe from 1971-2000 to 2071-2100 under high emissions scenario[19] [Colour figure can be viewed at wileyonlinelibrary.com]

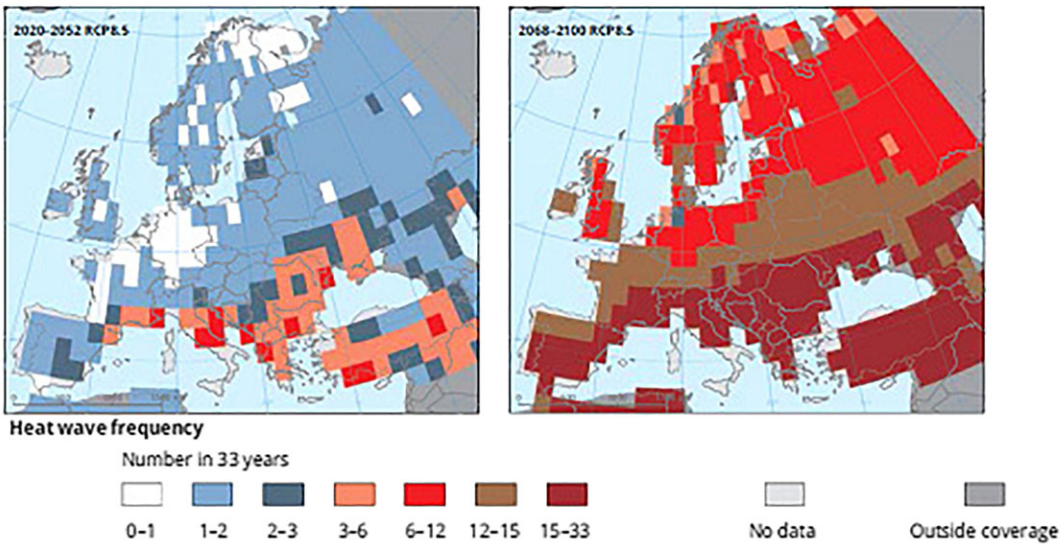

FIGURE 6 Number of very extreme heat waves in future climate across Europe under the high emissions scenario[20] [Colour figure can be viewed at wileyonlinelibrary.com]

agreed on a global climate agreement at the Paris climate conference (COP21) in December 2015, which will be legally binding and effective in 2020 or sooner.[27]

Regarding the mitigation, the governments in the Paris Agreement agreed on maintaining the global temperature rise much lower than 2°C compared with the mid-1800 levels, peaking the global GHG emissions as soon as possible and undertaking further reductions after peaking. However, we know that even if we achieve the 2°C increase limit, many places around the globe will experience relatively higher increases in temperature, and thence climate change will have many different consequences across the globe. Consequently, adaptation measures to the change as well have been considered within the UNFCCC as a significant policy pillar, which is indeed an additional and complementary tool to the mitigation. Regarding the adaptation, at the Paris COP21[27], governments agreed on establishing and improving adaptation capacity and resilience while eliminating vulnerability as much as possible, strengthening societies' ability to deal with the impacts, involving in national adaptation planning processes, and providing developing countries with continued and enhanced international support for adaptation.

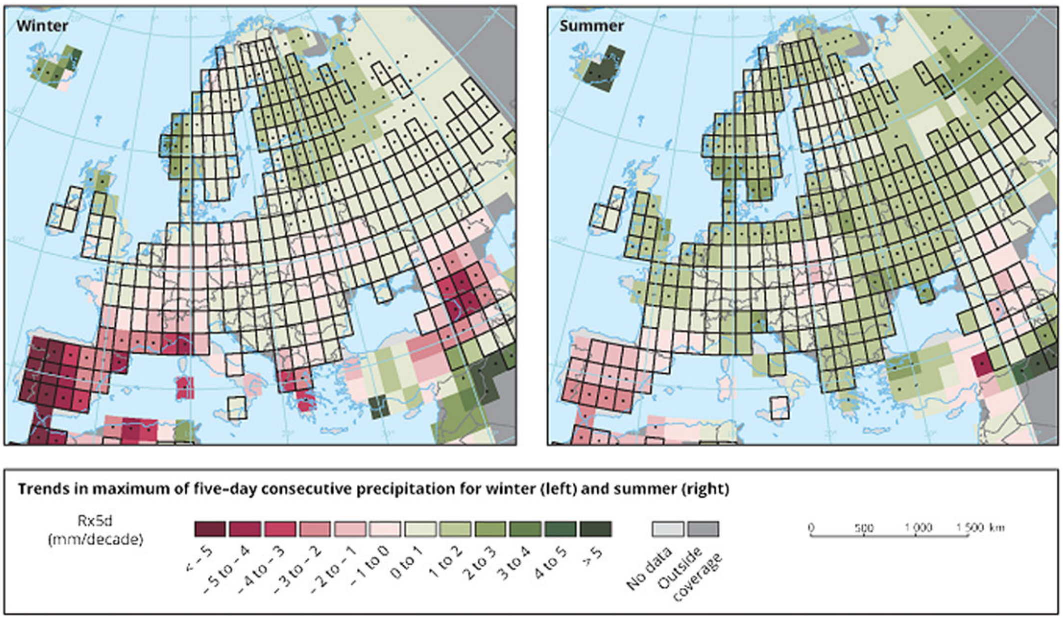

FIGURE 7 Observed trends in maximum annual 5-day consecutive precipitation across Europe in winter and summer[21] for the period of 1960-2015 [Colour figure can be viewed at wileyonlinelibrary.com]

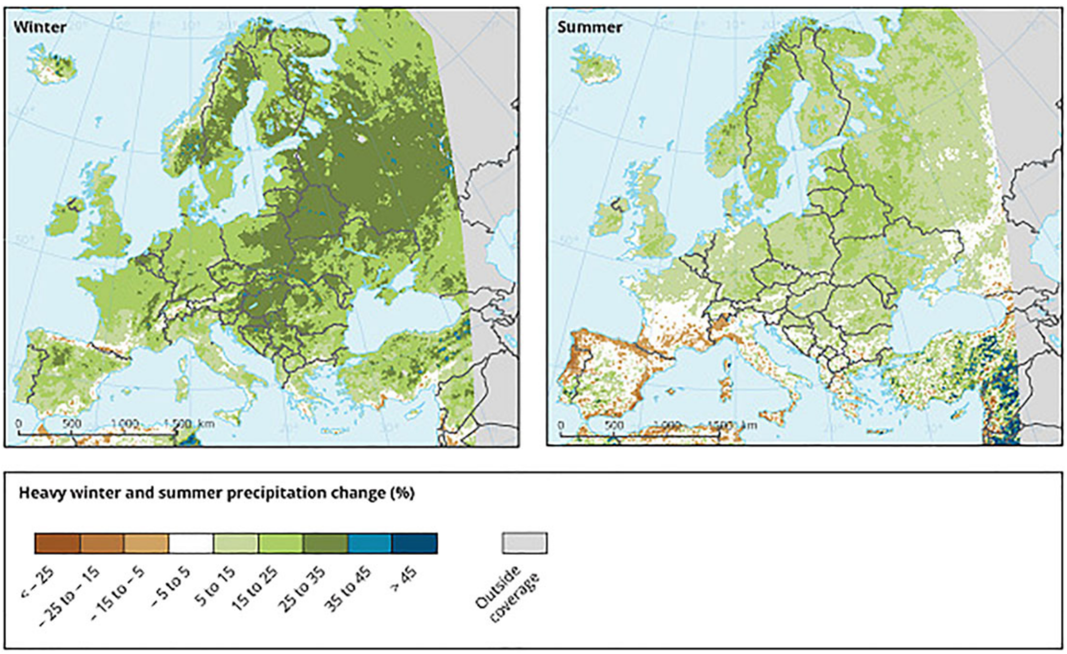

FIGURE 8 Projected changes in heavy precipitation in winter and summer across Europe over 2071-2100 compared with 1971-2000 for the high emissions scenario[22] [Colour figure can be viewed at wileyonlinelibrary.com]

Thereby, the European Union (EU) climate change mitigation policy, for instance, aims reducing its GHG emissions progressively up to 2050. The 2030 climate and energy framework, which is not yet adopted but included in EC,[28] proposes the following three key targets for 2030, namely, 40% cut in GHG emissions (from those of 1990), 27% of EU final energy consumption from renewables, and compared with baseline, 27% improvement in energy efficiency. The goal of the 2050 low-carbon roadmap[29] is to cut the EU emissions quite ambitiously (by 80% to 95%). And all the above-mentioned mitigation and adaptation measures will provide tremendous opportunities globally for developing innovative products, processes, services, and policies.

3 | IMPACTS OF CLIMATE CHANGE

3.1 | Impacts of climate change on environmental systems

Changes in climatic variables have direct effects on physical, chemical, and biological characteristics of environmental systems and ecosystems. About third of the Earth's surface is occupied by the oceans, which intimately interact with the atmosphere and therefore impact weather patterns both regionally and globally. Therefore, changes in the atmosphere can in return change the properties of the oceans. Changes in ocean properties potentially caused by elevated GHG concentrations, such as acidification and warming, can have substantial influences on marine ecosystems, productivity, and biodiversity and therefore ecosystem-service provision.[30] GHG concentrations (such as CO_2 concentration) have increased substantially and hence are now trapping more heat within the atmosphere. Majority of the trapped heat is stored by the oceans, where it eventually impacts ocean surface temperatures, ocean heat content and salinity, oceanic circulations, sea ice cover, and sea levels. The oceans also serve as carbon sinks, absorbing huge amounts of CO_2 from the atmosphere and therefore mitigating the magnitude of climate change. And, as a consequence of increasing levels of dissolved carbon, every passing year, the pH levels of seawaters are declining. All these changes will eventually have significant impacts on marine biodiversity and thence modify marine ecosystem productivity, functioning, and ecosystem-service provision.

Moreover, projected climate change threatens human and natural systems globally along coastal regions and on islands. Today, we have more than enough evidence in hand showing an increasing rate of GMSL rise during recent decades. Sea level rise is expected to be a serious concern for many more years due to the dynamics of climate system, even if GHG emissions and temperature are stabilized. Some recent model-based assessments have demonstrated an upper limit for the GMSL rise in the range of 1.5 to 2.0 m in the 21st century.[31] Unless we adopt additional adaptation measures, increased frequency and intensity of storm surges, projected sea level rise, and the consequential coastal erosion will lead to significant ecological and economic damages, as well as other societal problems along low-lying coastal areas globally.

There is an intimate relationship between water and climate. And again, we have more than enough evidence suggesting that the global water cycle has already been affected by the changes in climate. We now have huge temporal changes in river flows resulting in more often and much severe floods and droughts varying spatially. And even worse, it is projected that droughts will be more often and more severe and will last longer in many regions around the globe. Moreover, the water temperatures of surface waters have risen due to the changes in climate, impacting the seasonal ice cover as well.

Furthermore, the changes in climate are affecting terrestrial ecosystems and biodiversity and are expected to become a prominent forcing function (stressors) for biodiversity and ecosystem change in the coming decades.[32] The changes in climatic variables are expected to have multiple effects on biodiversity (both positive and negative) at different levels (genetic, species, and ecosystem). These changes include not only the changes in species abundance and phenology but also the shifts in distribution of ecosystems and species, as well as the increased risk of extinctions for some species. Climate change potentially impacts organic carbon contents of soils as well, and in turn, these changes have an impact on climate change. Soil erosion is already expanding globally, jeopardizing the vital services of one of our precious resource, soil, provides. Overall, the changes in climatic variables will have unavoidable consequences on the properties of habitats, the individual species themselves, and the complex interactions between species. Human efforts to mitigate and adapt to climate change could also speed up the direct impacts.[33] The ability of ecosystems to provide multiple services to human beings will eventually be affected by the changes in climate. The species responses to the changes in climatic variables will surely be a function of their adaptation strength, which includes modified migration and colonization as well. If all the above-mentioned response mechanisms of species fail, thence the species might gradually disappear and eventually become extinct. Our own well-being as well clearly depends on the environmental systems, which provide us with food, energy, clean water, and clean air as well as all sorts of interactions (physical, intellectual, and cultural) with nature. However, the ecosystems, habitats, and species that provide these vital services to us are dangerously under stress and are being lost or degraded by our own activities.[34] Climate change significantly influences ecosystems, their biodiversity, and consequently their capacity to provide services for our well-being and is increasingly exacerbating the impact of other anthropogenic forcing functions, especially in natural and partly natural ecosystems. The relative significance of climate change compared with other forcing functions clearly depends on the environmental sector (terrestrial, freshwater, marine) and geographical region.

3.2 | Impacts of climate change on society and innovation

Changes in climatic variables and their consequential impacts on environmental systems discussed above have various impacts on our overall activities and well-being. This section primarily focuses on climate-sensitive agriculture and energy sectors and relevant innovations.

3.2.1 | Invention and innovation

The first development of a new product, process, service, or policy is called as invention. If this new thing is commercialized, then we talk about innovation. Innovation can be an idea, a brand new creation (invention) of something (product, process, service, or policy), or an introduction of an existing thing to a new place (a firm, a region, a country, etc), also known as technology transfer. In short, not every invention is an innovation; rather, an idea or invention that creates some kind of value is considered as an innovation, which eventually generates business opportunities and hence economic growth. Climate change serves as a forcing function to induce the generation of new ideas, inventions, and innovations including technology transfer innovations in an incremental nature in both agricultural and energy sectors.

3.2.2 | Impacts of climate change on agriculture and agricultural innovation

Different climatic variables have direct impacts on the cultivation, productivity, and quality of crops. The parameters frequently employed for assessing the effects of climatic variables on agriculture are (a) *growing season* of a particular crop at a particular location—dictated by temperature; (b) *agrophenology*, which determines the annual crop cycle timing and therefore determines the productivity of a specific crop; (c) *water-limited crop yield*, which deals with potential fluctuations in crop productivity under different climatic variables (temperature, precipitation, etc); and (d) *crop water requirement*, which is the water demand for obtaining maximum yields.

Overall, the above-mentioned parameters deal with the biophysical consequences of the changes in temperature and precipitation. We know that atmospheric CO_2 levels as well directly influence crop yield and quality through photosynthesis and water use. Increased CO_2 concentrations in plants stimulate plant photosynthesis in crops that have the C3 photosynthesis pathway, except crops such as maize and *Miscanthus*, which have a different pathway called the C4 photosynthesis pathway. As a result, we would expect much higher C3 crop yields under elevated atmospheric CO_2 concentrations (aka CO_2 fertilization). For instance, under the high emissions scenario, when CO_2 fertilization effect is included, Figure 9 shows that two different crop models generally project a yield increase in water-limited winter wheat (a C3 crop) in most areas of Europe. The extent to which photosynthesis is stimulated and yield is increased by elevated CO_2 concentrations however, as explained above, depends on the crop species and other environmental conditions (eg, available photosynthetically active radiation). Overall, crop yield is determined by the interaction between changes in climate, atmospheric CO_2, and technology. It should be emphasized that livestock productions are also important and influenced by the changes in climatic variables. Temperature and humidity affect the productivity and well-being of animals directly. Additionally, we can also talk about various indirect impacts through, for instance, animal disease vectors and animal feed production and abundance.

As mentioned earlier, climate change is actually happening and is already impacting agriculture.[36] For instance, climate change has been adversely impacting wheat yields even though we have had tremendous advances in crop breeding.[37] And this impact will continue in the future[36]; however, the impacts will have spatial[38] and temporal[39] variations. It is the general view that, for instance, crop productivities in northern Europe will get better because of longer growing seasons and wider frost-free windows predicted (Figure 10). In southern Europe, however, the crop productivities are expected to be adversely impacted by climate change mainly due to aggravated heat events and projected drops in precipitation and therefore water availability.[40] Figure 11 further demonstrates the projected meteorological draught frequencies, which will mostly be the case under the high emissions scenario, forecasting the worst projected droughts in southern Europe, particularly the eastern Mediterranean, the Iberian Peninsula, and southern Italy.[42] Not only the extreme climatic events but also pests and diseases are generally expected to widen the yield variability.[43] As well with the expanding global population and increasing wealth, the growing concern for global food security is exacerbated by conflicting demands on scarce land and water resources—also needed for other competing uses, including biofuels, biodiversity, recreational activities, and others,[44] and therefore, considerable differences will be observed in adaptive capacity among regions and farms depending on their specialization and many other characteristics.[45] Intensive production systems are, for instance, generally not too vulnerable to climate change because the given changes would have modest impacts, and as well farm

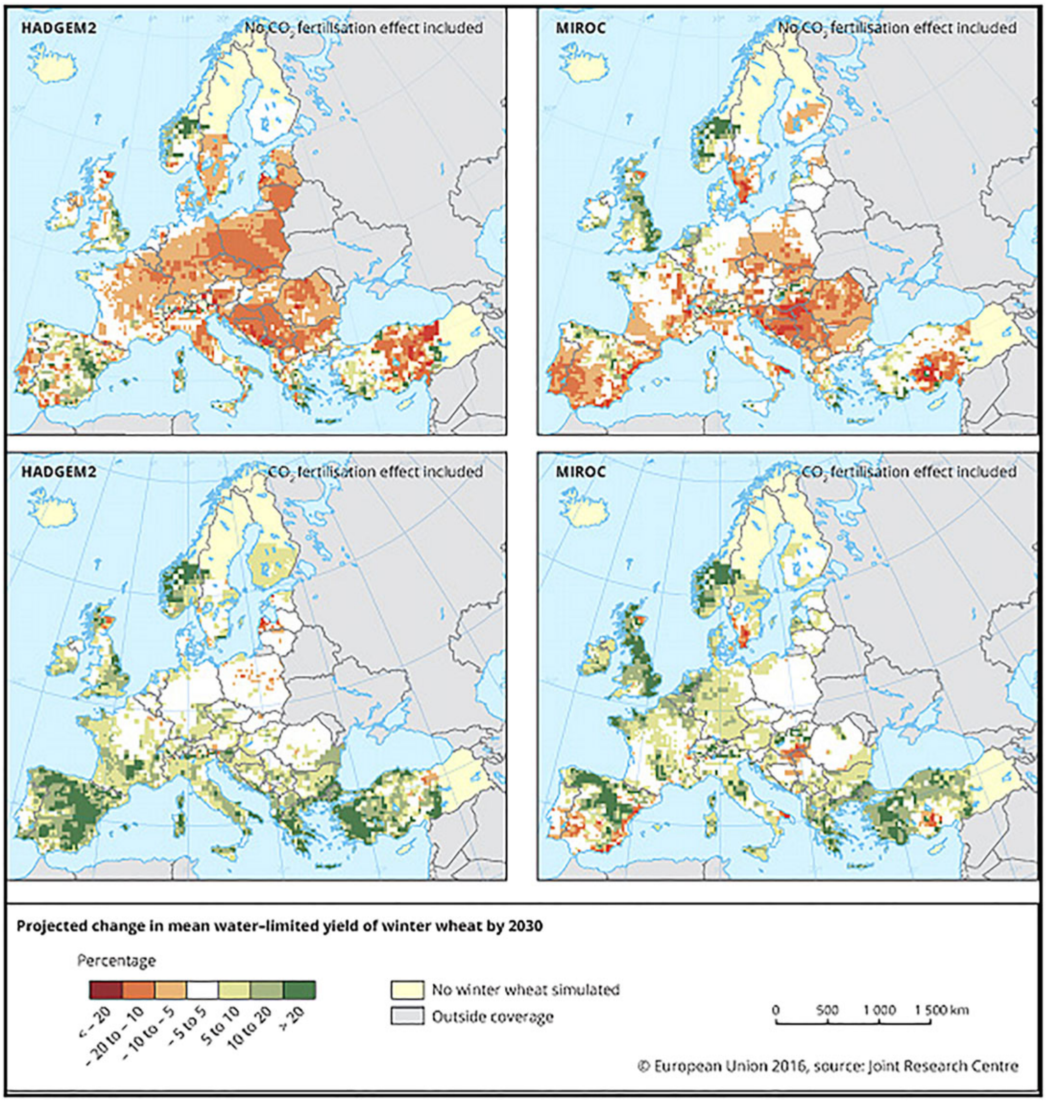

FIGURE 9 Projected changes in water-limited yield of winter wheat across Europe over the period of 2000-2030.[35] Top: no CO_2 fertilization effect included. Bottom: CO_2 fertilization effect included for the high emissions scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

managers have plenty of resources to adapt to these changes very fast and quite effectively.

Within the global agricultural domain, so many innovative approaches or examples can be given, but probably one of the best leading institutions developing innovative technologies and products in the agri-food domain is the International Rice Research Institute (IRRI), headquartered in the Philippines. The IRRI has been working on developing rice varieties, which can perform better under the projected changes in our climate system. These varieties are able to resist harsh environmental stress conditions like drought, submergence, extreme heat, cold, and numerous adverse soil conditions. The stress conditions can be caused or elevated by extreme climatic events like drought, heat waves, flooding, or rising sea levels, all of which adversely affect rainfed rice production that eventually impacts the livelihood of many millions of poor population in Asia alone. Within the framework of the aforementioned efforts, the IRRI has been trying to address numerous aspects of climate change in rice production systems. The main goal of its adaptation agenda is to develop climate change-ready rice and relevant crop management practices that can tolerate the impacts of elevated temperatures and other climatic forcing functions. Its mitigation agenda, however, mainly targets reducing the carbon footprint of irrigated rice.

It must also be emphasized that the emerging field of precision agriculture offers tremendous potential for an integrated (environmental, economic, and social) understanding of the interconnection between our natural environment and our activities. Every passing day, engineers and scholars are developing novel target-application technologies for variable applications of agro-chemicals and other site-specific agro-production technologies for

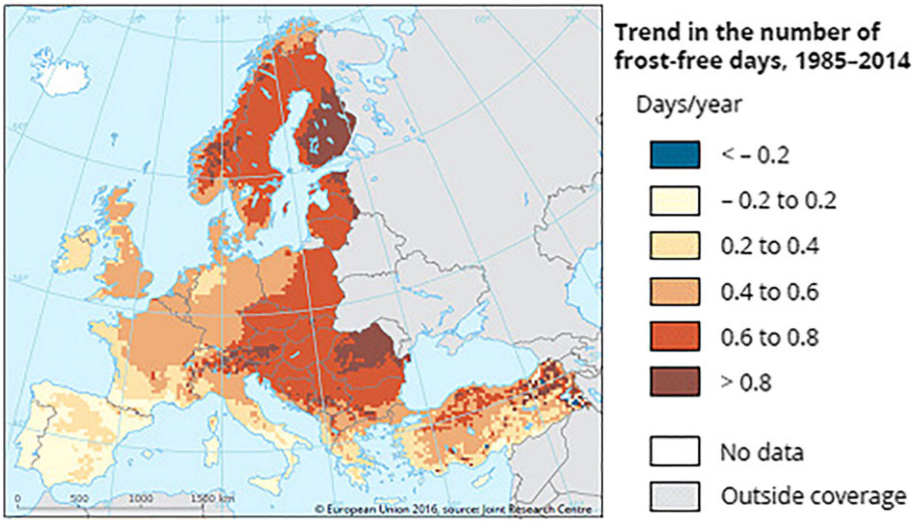

FIGURE 10 Observed trend in the number of frost-free days across Europe[35] over the period of 1985-2014 [Colour figure can be viewed at wileyonlinelibrary.com]

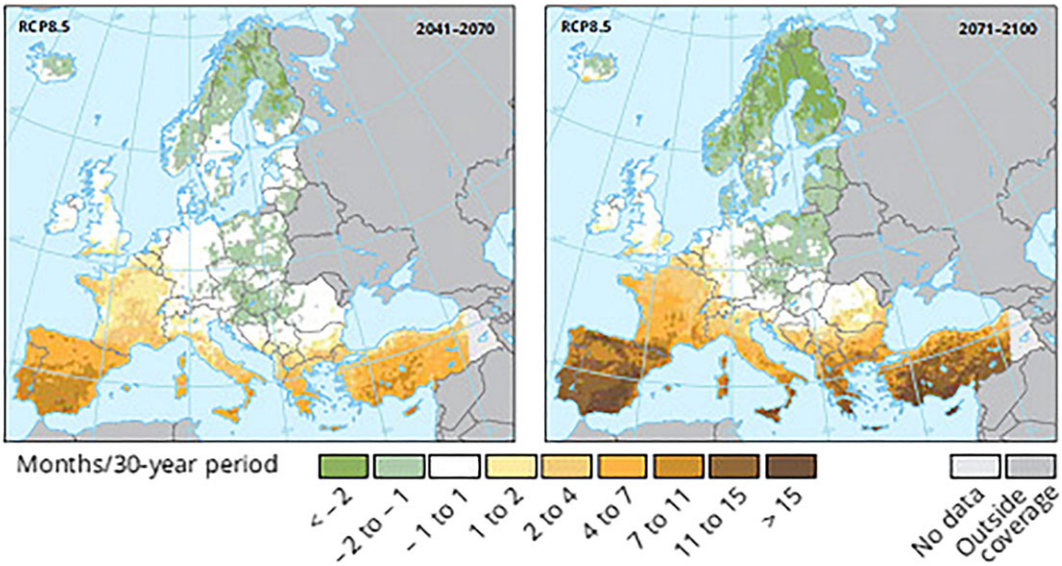

FIGURE 11 Projected frequency of meteorological draught across Europe over the period of 2041-2070 and 2071-2100 compared with that of 1971-2000 for the high emission scenario[41] [Colour figure can be viewed at wileyonlinelibrary.com]

irrigation, planting, crop monitoring, harvesting, etc. In summary, precision agriculture technologies have tremendous environmental, economic, and social benefits. Such technologies can reduce the overall energy consumption, the GHGs, and the release of excess agrochemicals into the environment, which ultimately result in resource efficient, cost-effective operations, and reduced carbon footprints, eventually sustaining our operations and rural communities.

It was indicated by the recent Agricultural Model Intercomparison and Improvement Project (AGMIP) that a 20% (mean) food price rise could be caused by climate change by the year 2050 globally, demonstrating a large range from 0 to 60%.[46] Since the impacts will be spatially specific, the adaptations as well will have to be spatially specific with local framework in terms of climate, soils, and farming systems. As the relationship between agricultural production and climate change has been discussed and is quite clear now, we can say that there exists a reciprocal relationship between climate change and agri-food innovation. Each and every indicator and potential impacts provided above and the required mitigation and adaptation will exert further stress and speed up agri-food innovation, generating tremendous opportunities in multiple dimensions at different levels, covering technical, methodological, managerial (eg, crop and inventory managements), and institutional innovations (eg, biotechnology, precision technologies, novel methodologies, insurance, and policy). Just to name a few, these dimensions will frequently reveal innovations in crop and inventory management (multiple crops a year, new crops, machinery, and systems), water-limited, drought-resistant, heat and salt-tolerant and longer season cultivars. In return, complementing other forms of climate change mitigation and adaptation measures, agri-food innovation will become one of the leading societal reactions to climate change, speeding up the mitigation and adaptation processes. Facilitating carbon-neutral bio-economy, preventing or facilitating population migrations, enhancing trade and insurance efficiency, and increasing agri-food inventory feasibility, and many others can be cited as specific examples of such societal responses.

3.2.3 | Impacts of climate change on energy and energy innovation

All dimensions of life are supported by energy. Energy sector is quite a large sector, which covers series of steps from production to utilization. Energy production, transformation, and consumption are mostly responsible for human-caused GHG emissions; therefore, efforts directed towards decreasing inefficiencies in return could reduce environmental impacts. Dincer and Rosen[47] studied the relationships between energy and environmental impacts and stated that efforts to increase efficiency within the scope of exergy methods lead to increased exergy efficiency, which has tremendous importance for practical applications. There is a desperate need to greenize the existing energy systems considering various factors like environmental impacts, system efficiencies, and the economics, which will ultimately solve many challenging environmental problems, particularly global warming, and help us to achieve better sustainability.[48,49]

Energy supply and demand are susceptible to climate change, especially to the temperature changes. Globally speaking, the main focus on energy demand is on electricity and in particular on residential electricity needs. Domestic space heating requirements are quite often provided by electrical energy while cooling almost all the time is performed by electricity. Consequently, changes in heating and cooling demands directly impact the demand for electrical energy. Increased demands for electricity in summers typically coincide with the shortage of proper power plant cooling water availability in hot environments.[50] Space heating and cooling energy requirements make up a big portion of total energy consumption in many parts of the world. Heating degree-days (HDDs) and cooling degree-days (CDDs) are the proxies employed for determining the energy demand for heating and cooling, respectively, of a residential dwelling or a business. Both of these variables are derived from the measured daily outside air temperatures. At a particular location, the heating and cooling needs of a given building are proportional to the number of HDDs and CDDs at that location. HDDs and CDDs are calculated employing daily mean outside temperatures at that location and a base temperature—below or above which a building either needs heating or cooling. The baseline temperatures today are quite different from what was developed for buildings in the 1940s (still in use though), and our buildings today are much tighter, more insulated, and have more internal heat sources. Therefore, in order to accurately determine the energy demands for heating and cooling and hence gauge the relevant climate change impacts, new baseline temperatures need to be developed for both heating and cooling. We use the daily mean temperatures ($T_{mean} = [T_{max} - T_{min}]/2$) in HDD and CDD calculations even though the maximum temperature is more relevant for cooling rather than the mean temperature and while the heating is more related to the minimum temperature. Further, long-term temperature data closer to our present time should also be utilized for more reliable calculations of HDD and CDD and therefore for future energy assessments. In the light of climate change, Yildiz et al[51] as well stressed the importance of updating engineering weather design parameters and performing spatiotemporal analyses; they developed up to date engineering weather design parameters for a particular region for designing more efficient HVAC systems. All these discussions make the insights clear and provide opportunities for methodological innovation driven by climate change, for instance. Generally speaking, climate change is reducing the space heating needs while increasing the needs for cooling globally. Isaac and van Vuuren[52] studied the projected future energy use for residential heating and air-conditioning under the light of climate change. They reported that global heating energy requirement will increase until the year 2030 and then will stabilize. The global residential cooling energy requirement on the other hand was forecasted to increase over the period of 2000 to 2100 due to the changes in climate and the growth in income. However, they determined a very small net effect on global energy consumption because of the compensation between heating and cooling. Under the studied scenario, considerable individual impacts on heating and cooling energy demands were observed in this study, showing a decreased demand for heating by approximately 34% globally by the year 2100 and an increased demand for cooling by approximately 72% globally. When we look at the picture at regional scales, however, considerably significant projected impacts of climate change are reported. For instance, the energy demand for space cooling in South Asia is projected to increase half fold. In this line, Figures 12 and 13 show a declining trend in HDDs and an increasing trend in CDDs in Europe. However, these proxies are not the only parameters responsible for determining future heating and cooling energy demands; technical and socioeconomic factors will also play a significant role in future energy demands.

Impacts of climate change on electrical energy generation, particularly through the observed and projected changes in water availability, have been reported and highlighted in a number of studies. These impacts will obviously vary depending on the proportion of different sources in the energy mix and the specific geographical location. Spatial differences will be observed, and the impacts will surely vary depending on the relevant technology. Both production increases and decreases are projected around the world.[54,55] Climate change impacts on particularly renewable electricity production show quite a strong variability spatially.[56] Changed precipitation patterns or variability as a result of climate change could create much greater uncertainty when hydropower facilities are considered. Hydropower production might experience significant risks in some regions (eg, Alpine countries), while conditions in some other regions such as Scandinavia may get even better.[54,57] Climate change–induced erosion and sediment displacement could increase silting of sediment into reservoirs as well, eventually affecting hydropower production. Climate change impacts on wind power generation as well might

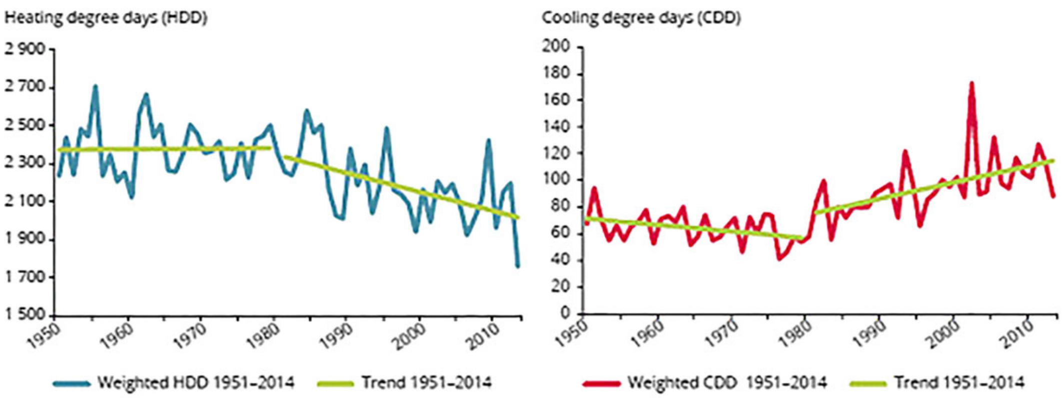

FIGURE 12 Time series of population-weighted heating and cooling degree days across Europe[53] averaged over the period of 1951-2014 [Colour figure can be viewed at wileyonlinelibrary.com]

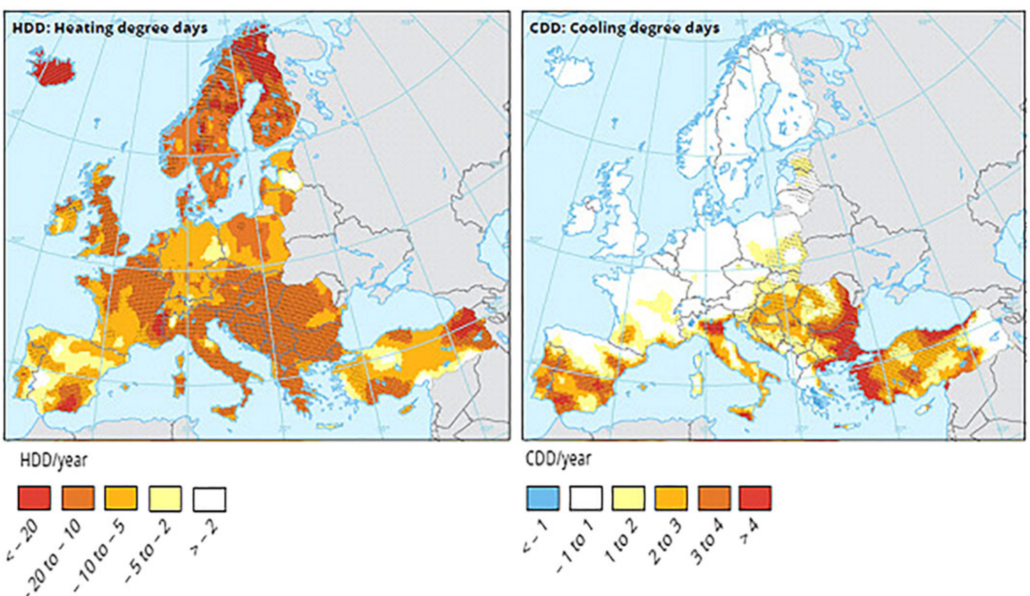

FIGURE 13 Observed trends in heating and cooling degree days across Europe[53] over the period of 1981–2014 [Colour figure can be viewed at wileyonlinelibrary.com]

be negative over some regions (eg, the Mediterranean) reducing power potential, while other regions (eg, northern Europe) might benefit from the changes.[58] Regional studies on solar power generation, on the other hand, show very limited or neutral effects overall.[42,59] It should however be emphasized that fossil-fired and nuclear electricity generators are quite sensitive to increased air temperature, increased cooling water temperature, and reduced water availability, each of which reduce the power plant efficiencies. Nuclear power plants are particularly susceptible to climate change, and France would be facing the highest risk in this regard as the major portion of its electricity generation is provided by the nuclear power plants. The economic damage due to the decreased availability of nuclear power because of climate change could be quite dramatic, and this could be as high as tens of billions of euros per year by 2100 under the high emissions scenario.[54,60] Overall, we can expect significant impacts of climate change on electricity generation, paving the way for worse operating conditions for hydro, thermal, and nuclear power plants. The projected losses in generation efficiencies of thermal and nuclear power plants may impact their competitiveness, and therefore, it would result in an increased proportion of renewables in the energy mix.[61] Other renewable energy supplies might also be harmed by the projected climate change, particularly through the bioenergy production. If a novel example were to be given in the bioenergy domain, then probably biofuels production from microalgae would be one of the front-runners. Microalgae need CO_2 to undergo photosynthesis, and therefore, microalgae cultivation forms a continuous living carbon sink. And different waste streams (power plants and others) can supply the CO_2 required by the rapid-growing microalgae facilitating successful GHG mitigation. The generated biomass can then be converted to biofuels, nutraceuticals, pharmaceuticals, and also a fuel source for generating electricity.[62]

On the other hand, extreme weathers such as storms, extreme wind gusts, and ice storms could also impact energy infrastructure, such as transmission and distribution lines, along with renewable energy generating facilities. Renewable energy based electricity generators are quite sensitive to potential extreme storm gusts, which can easily damage wind turbines, for instance. Increased flooding events as well could pose dangers for power stations, transmission lines, and substations. When we consider the increasing dependence on electricity and the shift of the energy mix towards much more vulnerable technologies, it would be much easier to see how susceptible the energy production and transmission infrastructure are to climate change.[63] Also, the national energy networks are highly interconnected today, and therefore, the vulnerability of energy infrastructures does not stay within, rather moves beyond the national boundaries.[63] Generally speaking, electricity transmission lines and pipelines are engineered with quite a high tolerance to extreme weather events, which also adds further safety margins for future climate change. After the Fukushima accident, however, the results of stress tests on nuclear power plants in Europe, for instance, stated that further improvements can be made for extreme weather events.[29,64] The International Atomic Energy Agency has developed specific guidelines for good practice against extreme events (including extreme weather events), which would be followed by a number of different countries.[65] Moreover, sea level rise due to climate change threatens coastal energy infrastructures like oil, gas or liquefied natural gas tanker terminals, and nuclear power stations. The risks to coastal energy infrastructure could, to some extent, be mitigated with a well-planned adaptation measures and a high-level awareness of the threats.[66]

For achieving sustainability, Dincer and Acar[67] focused on clean energy options and discussed all sorts of hopes and difficulties from different dimensions, including energetic, environmental, and socioeconomics. They evaluated possible clean-energy systems and comparatively assessed renewable energy sources and ranked them based on their outputs. In the second part of their study, they introduced innovative multigeneration systems and discussed their potential benefits along with other innovative approaches provided in the literature. Renewable energy-based integrated systems clearly offer multiple advantages and outputs, which reduce the overall energy needs, cost, and emissions, ultimately improving the overall efficiencies tremendously. In another study[68], comprehensive analyses of energetic, exergetic, and environmental characteristics of drying systems were studied. Multiple issues were innovatively assessed, and the authors identified and emphasized exergy analysis as a proper tool for improving resource consumption efficiency as well as determining the wastes and losses in drying systems. Furthermore, while innovative methodologies involving life cycle assessments (LCA), exergoeconomic, and exergoenvironmental analyses provide us with excellent tools for better managing the environment and maintaining a sustainable development, it can be stated that potential utilization of hydrogen energy, for instance, will be providing a more sustainable energy option and therefore tons of opportunities for innovation. In depth information on these approaches and views can be found in Dincer.[49,69]

As emphasized earlier, the mitigation and adaptation will be spatially specific with local framework with respect to climate change, infrastructure, and energy systems. As in the case of climate change and agri-food innovation, there exists a reciprocal relationship between the changes in climate and energy innovation. Each and every potential impact of climate change mentioned-above and the required mitigation and adaptation will be exerting further pressure speeding up energy innovation, providing ample opportunities in multiple dimensions at different levels, covering technological, methodological, managerial, and institutional innovations (eg, energy production and efficiency technologies, novel methodologies, proper inventories and energy infrastructures, energy management, safety, insurance, and policy). In return, complementing other forms of mitigation and adaptation to climate change, energy innovation will become a vital societal response to climate change speeding up the mitigation and adaptation processes, for instance, facilitating carbon-neutral and renewable energy production, enhancing energy efficiency, trade and insurance efficiency, and increasing energy inventory feasibility.

4 | CONCLUSIONS

Climate change is happening and is expected to continue for many years in the future. Strengthening the resilience of agri-food and energy production systems to the changes in climate and therefore improving the adaptive capacity are vital for the global population. Furthermore, reducing the GHG emissions due to fossil fuels production and consumption is crucial as well. And agri-food and energy sectors have tremendous potentials for reducing operational inefficiencies and GHG emissions. Every potential impact of climate change and the consequential mitigation and adaptation measures are becoming more urgent than ever and exerting further pressures on our daily lives and therefore providing wide open business horizons at different levels and speeding up the agri-food and energy innovations as crucial societal responses, which will be spatially specific with local contexts covering not only technological innovations but also methodological, managerial, and institutional innovations, particularly in biotechnology, precision technologies, agricultural and energy production, management, efficiency, safety, insurance, and policy domains. It can be concluded that climate change serves as a forcing function to induce the generation of new ideas, inventions, and innovations including technology transfer innovations in an incremental nature in both agricultural and energy sectors. As a result, new firms, regions, or populations will at first be adopting transferred technologies and approaches from other places, if available, and then, these new places and populations will take the existing products, processes, services, and policies to newer levels and horizons with their own added inventions and innovations. Due to the reciprocal relationships between climate change and agri-food and energy innovations, in return, complementing the other forms, such innovations will speed up the climate change mitigation and adaptation processes.

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