REVIEW ARTICLE

Climate change and its impact on biodiversity and human welfare

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Abstract

Climate change refers to the long-term changes in temperature and weather due to human activities. Increase in average global temperature and extreme and unpredictable weather are the most common manifestations of climate change. In recent years, it has acquired the importance of global emergency and affecting not only the wellbeing of humans but also the sustainability of other lifeforms. Enormous increase in the emission of greenhouse gases (CO_2, methane and nitrous oxide) in recent decades largely due to burning of coal and fossil fuels, and deforestation are the main drivers of climate change. Marked increase in the frequency and intensity of natural disasters, rise in sea level, decrease in crop productivity and loss of biodiversity are the main consequences of climate change. Obvious mitigation measures include significant reduction in the emission of greenhouse gases and increase in the forest cover of the landmass. Conference of Parties (COP 21), held in Paris in 2015 adapted, as a legally binding treaty, to limit global warming to well below 2 °C, preferably to 1.5 °C by 2100, compared to pre-industrial levels. However, under the present emission scenario, the world is heading for a 3–4 °C warming by the end of the century. This was discussed further in COP 26 held in Glasgow in November 2021; many countries pledged to reach net zero carbon emission by 2050 and to end deforestation, essential requirements to keep 1.5 °C target. However, even with implementation of these pledges, the rise is expected to be around 2.4 °C. Additional measures are urgently needed to realize the goal of limiting temperature rise to 1.5 °C and to sustain biodiversity and human welfare.

Keywords Biodiversity · Climate change · Deforestation · Emission of greenhouse gases · Human welfare · Ocean acidification

Introduction

Climate change refers to long-term changes in local, global or regional temperature and weather due to human activities. For 1000s of years, the relationship between lifeforms and the weather have been in a delicate balance conducive for the existence of all lifeforms on this Planet. After the industrial revolution (1850) this balance is gradually changing and the change has become apparent from the middle of the twentieth century. Now it has become a major threat to the wellbeing of humans and the sustainability of biodiversity. An increase in average global temperature, and extreme and unpredictable weather are the most common manifestations of climate change. It has now acquired the importance of global emergency. According to the report of the latest Intergovernmental Panel for Climate Change (AR6 Climate Change 2021), human-induced climate change as is prevalent now is unprecedented at least in the last 2000 years and is intensifying in every region across the globe. In this review the drivers of climate change, its impact on human wellbeing and biodiversity, and mitigation measures being taken at global level are briefly discussed.

Drivers of climate change

Emission of green-house gases

Steady increase in the emission of greenhouse gases (GHGs) due to human activities has been the primary driver for climate change. The principal greenhouse gases are carbon dioxide (76%), methane (16%), and to a limited extent nitrous oxide (2%). Until recent decades, the temperature of the atmosphere was maintained within a reasonable range as some of the sunlight that hits the earth was reflected back

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into the space while the rest becomes heat that keeps the earth and the atmosphere warm enough for the sustenance of life forms. Accumulation of greenhouse gases combine with water vapour to form a transparent layer in the atmosphere that traps infrared radiation (net heat energy) emitted from the Earth's surface and reradiates it back to Earth's surface, thus contributing to the increasing temperature (greenhouse effect). Methane is 25 times and nitrous oxide 300 times more potent than CO_2 in trapping heat. Until 2019, the US, UK, European Union, Canada, Australia, Japan and Russia were the major CO_2 producers and were responsible for 61% of world's emissions. Now, China produces the maximum amount of CO_2 (27%) followed by USA (11%) and India (6.6%); on per capita basis, however, India stands ninth.

The emission of GHGs is largely due to the burning of fossil fuels (coal, oil and natural gas) for automobiles and industries which result in carbon emissions during their extraction as well as consumption. The amount of CO_2 in the atmosphere before the industrial revolution used to be around 280 ppm and now it has increased to 412 ppm (as of 2019). Increase in the atmospheric temperature also leads to an increase in the temperature of the ocean. The oceans play an important role in the global carbon cycle and remove about 25% of the carbon dioxide emitted by human activities. Further, some CO_2 dissolves in the ocean water releasing carbonic acid which increases the acidity of the sea water. Rising ocean temperatures and acidification not only reduce their capacity to act as carbon sinks but also affect ocean ecosystems and the populations that relay on them.

Increasing demand for meat and milk has led to a significant increase in the population of livestock and conversion of enormous amount of the land to pasture and farm land to raise livestock. Ruminant animals (largely cows, buffaloes and sheep) produce large amounts of methane when they digest food (through enteric fermentation by microbes), adding to the greenhouse gases in the atmosphere (Sejiyan et al. 2016). To produce 1 kg of meat it requires 7 kg of grain and between 5000 and 20,000 L of water whereas to produce 1 kg of wheat it requires between 500 and 4000 L of water (Pimentel and Pimentel 2003). Anaerobic fermentation of livestock manure also produces methane. According to Patrick Brown, our animal farming industry needs to be changed; using readily available plant ingredients, the nutritional value of any type of meat can be matched with about one twentieth of the cost (See Leeming 2021).

The main natural source of nitrous oxide released to the atmosphere (60%) comes from the activity of microbes on nitrogen-based organic material from uncultivated soil and waste water. The remaining nitrous oxide comes from human activities, particularly agriculture. Application of nitrogenous fertilizers to crop plants is a routine practice to increase the yield; many of the farmers tend to apply more than the required amount. However, it results in nitrous oxide emissions from the soil through nitrification and denitrification processes by microbes. Both synthetic and organic fertilizers increase the amount of nitrogen available in the soil to microbial action leading to the release of nitrous oxide. Organic fertilizers, however, release nitrogen more slowly than synthetic ones so that most of it gets absorbed by the plants as they become available. Synthetic fertilizers release nitrogen rapidly which cannot be used by plants right away, thus making the excess nitrogen available to microbes to convert to nitrous oxide. Presently CO_2 concentration in the atmosphere is higher than at any time in at least 2 million years, and methane and nitrous oxide are higher than at any time in the last 800,000 years (AR6 Climate Change 2021).

Permafrost (permanently frozen soil), widespread in Arctic regions of Siberia, Canada, Greenland, Alaska, and Tibetan plateau contains large quantities of organic carbon in the top soil leftover from dead plants that could not be decomposed or rot away due to the cold. Global warming-induced thawing of permafrost facilitates decomposition of this material by microbes thus releasing additional amount of carbon dioxide and methane to the atmosphere.

Deforestation

Limited deforestation in early part of human civilization was the result of subsistence farming; farmers used to cut down trees to grow crops for consumption of their families and local population. In preindustrial period also, there was a balance between the amount of CO_2 emitted through various processes and the amount absorbed by the plants. Forests are the main sinks of atmospheric CO_2. After the industrial revolution, the trend began to change; increasing proportion of deforestation is being driven by the demands of urbanization, industrial activities and large-scale agriculture. A new satellite map has indicated that field crops have been extended to one million additional km^2 of land over the last two decades and about half of this newly extended land has replaced forests and other ecosystems (Potapov et al. 2021).

In recent decades the demands on forest to grow plantation crops such as oil palm, coffee, tea and rubber, and for cattle ranching and mining have increased enormously thus reducing the forest cover. According to the World Wildlife Fund (WWF), over 43 million hectares of forest was lost between 2004 and 2017 out of 377 million hectares monitored around the world (Pacheco et al. 2021). Amazon Rain Forest is the largest tropical rain forest of the world and covers over 5 million km^2. It is undergoing extensive degradation and has reached its highest point in recent years. According to National Geographic, about 17% of Amazon rain forest has been destroyed over the past 50 years and is increasing in recent years; during the last 1 year it has lost over 10,000 km^2. In most of the countries the forest cover is less than 33%, considered necessary. For example, India's

forest and tree cover is only about 24.56% of the geographical area (Indian State Forest Report 2019).

Impacts of climate change

Increase in atmospheric temperature has serious consequences on biodiversity and ecosystems, and human wellbeing. The most important evidences of climate change is the long term data available on the CO_2 levels, global temperature and weather patterns. The impacts of climate change in the coming decades are based on published models on the basis of the analysis of the available data. Comparison of the performance of climate models published between 1970 and 2007 in projecting global mean surface temperature and associated changes with actual observations have shown that the models were consistent in predicting global warming in the years after publication (Hausfather et al. 2019). This correlation between predicted models and actual data indicates that the models are indeed reliable in accurately predicting the global warming and its impacts on weather pattern in the coming decades and their consequences on biodiversity and human welfare.

Weather pattern and natural disasters

One of the obvious changes observed in recent years is the extreme and unpredictable weather, and an increase in the frequency and intensity of natural disasters. Brazil's south central region saw one of the worst droughts in 2021with the result many major reservoirs reached < 20% capacity, seriously affecting farming and energy generation (Getirana et al. 2021). In earlier decades, it was possible to predict with reasonable certainty annual weather pattern including the beginning and ending of monsoon rains; farmers could plan sowing periods of their crops in synchrony with the prevailing weather. Now the weather pattern is changing almost every year and the farmers are suffering huge losses. Similarly the extent of annual rainfall and the locations associated with heavy and scanty rainfall are no more predictable with certainty. Many areas which were associated with scanty rainfall have started getting much heavier rains and the extent of rainfall is getting reduced in areas traditionally associated with heavy rainfall. Similarly the period and the extent of snowfall in temperate regions have also become highly variable.

Increase in the frequency and intensity of natural disasters such as floods and droughts, cyclones, hurricanes and typhoons, and wildfires have become very obvious. Top five countries affected by climate change in 2021 include Japan, Philippines, Germany, Madagascar and India. Apart from causing death of a large number of humans and other animals, economic losses suffered by both urban and rural populations have been enormous. Deadly floods and landslides during 2020 forced about 12 million people leave their homes in India, Nepal and Bangladesh. According to World Meteorological Organization's comprehensive report published in August 2021 (WMO-No.1267), climate change related disasters have increased by a factor of five over the last 50 years; however, the number of deaths and economic losses were reduced to 2 million and US$ 3.64 trillion respectively, due to improved warning and disaster management. More than 91% of these deaths happened in developing countries. Largest human losses were brought about by droughts, storms, floods and extreme temperatures. The report highlights that the number of weather, climate and water-extremes will become more frequent and severe as a result of climate change.

Global warming enhances the drying of organic matter in forests, thus increasing the risks of wildfires. Wildfires have become very common in recent years, particularly is some countries such as Western United States, Southern Europe and Australia, and are becoming more frequent and widespread. They have become frequent in India also and a large number of them have been recorded in several states. According to European Space Agency, fire affected an estimated four million km^2 of Earth's land each year. Wildfires also release large amounts of carbon dioxide, carbon monoxide, and fine particulate matter into the atmosphere causing air pollution and consequent health problems. In 2021, wildfires around the world, emitted 1.76 billion tonnes of carbon (European Union's Copernicus Atmospheric Monitoring Service). In Australia, more than a billion native animals reported to have been killed during 2020 fires, and some species and ecosystems may never recover (OXFAM International 2021).

Sea level rise

Global warming is causing mean sea level to rise in two ways. On one hand, the melting of the glaciers, the polar ice cap and the Atlantic ice shelf are adding water to the ocean and on the other hand the volume of the ocean is expanding as the water warms. Incomplete combustion of fossil fuels, biofuels and biomass releases tiny particles of carbon (< 2.5 μm), referred to as black carbon. While suspended in the air (before they settle down on earth's surface) black carbon particles absorb sun's heat 1000s of times more effectively than CO_2 thus contributing to global warming. When black particles get deposited over snow, glaciers or ice caps, they enhance their melting further adding to the rise in sea level. Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years. Between 2006 and 2016, the rate of sea-level rise was 2.5 times faster than it was for almost the whole of the twentieth century (OXFAM International 2021). Precise data gathered

from satellite radar measurements reveal an accelerating rise of 7.5 cm from 1993 to 2017, an average of 31 mm per decade (WCRP Global Sea Level Budget Group 2018).

Snow accounts for almost all current precipitation in the Arctic region. However, it continues to warm four times faster than the rest of the world as the melting ice uncovers darker land or ocean beneath, which absorbs more sunlight causing more heating. The latest projections indicate more rapid warming and sea ice loss in the Arctic region by the end of the century than predicted in previous projections (McCrystall et al. 2021). It also indicates that the transition from snow to rain-dominated Arctic in the summer and autumn is likely to occur decades earlier than estimated. In fact this transition has already begun; rain fell at Greenland's highest summit (3216 m) on 14 August 2021 for several hours for the first time on record and air temperature remained above freezing for about 9 h (National Snow and Ice Sheet Centre Today, August 18, 2021).

In the annual meeting of the American Geophysical Union (13 December 2021) researchers warned that rapid melting and deterioration of one of western Antarctica's biggest glaciers, roughly the size of Florida, Thwaites (often called as Doomsday Glacier), could lead to ice shelf's complete collapse in just a few years. It holds enough water to raise sea level over 65 cm. Thwaites glacier is holding the entire West Antarctic ice sheet and is being undermined from underneath by warm water linked to the climate change. Melting of Thwaites could eventually lead to the loss of the entire West Antarctic Ice Sheet, which locks up 3.3 m of global sea level rise. Such doomsday may be coming sooner than expected (see Voosen 2021). If this happens, its consequences on human tragedy and biodiversity loss are beyond imagination.

The Himalayan mountain range is considered to hold the world's third largest amount of glacier ice after Arctic and Antarctic regions. It is considered as Asian water tower (Immerzeel et al. 2020); the meltwater from the Himalayan glaciers provide the source of fresh water to nearly 2 billion people living along the mountain valleys and lowlands around the Himalayas. These glaciers are melting at unprecedented rates. Recently King et al. (2021) studied 79 glaciers close to Mt. Everest by analysing mass-change measurements from satellite archives and reported that the rate of ice loss from glaciers consistently increased since the early 1960s. This loss is likely to increase in the coming years due to further warming. In another study, a tenfold acceleration in ice loss was observed across the Himalayas than the average rate in recent decades over the past centuries (Lee et al. 2021). Melting of glaciers also results in drying up of perennial rivers in summer leading to the water scarcity for billions of humans and animals, and food and energy production downstream. See level rise and melting of glaciers feeding the rivers could lead to migration of

huge population, creating additional problems. Even when the increase in global temperature rise is limited to 1.5 °C (discussed later), it generates a global sea-level rise between 1.7 and 3.2 feet by 2100. If it increases to 2 °C, the result could be more catastrophic leading to the submergence of a large number of islands, and flooding and submergence of vast coastal areas, saltwater intrusion into surface waters and groundwater, and increased soil erosion. A number of islands of Maldives for example, would get submerged as 80% of its land area is located less than one meter above the sea level. The biodiversity in such islands and coastal areas becomes extinct. China, Vietnam, Fiji, Japan, Indonesia, India and Bangladesh are considered to be the most at risk. Sundarbans National Park (UNESCO world heritage Site), the world's largest Mangrove Forest spread over 140,000 hectares across India and Bangladesh, is the habitat for Royal Bengal Tiger and several other animal species. The area has already lost 12% of its shoreline in the last four decades by rising see level; it is likely to be completely submerged. Jakarta in Indonesia is the fastest sinking city in the world; the city has already sunk 2.5 m in the last 10 years and by 2050, most of it would be submerged. In Europe also, about three quarters of all cities will be affected by rising sea levels, especially in the Netherlands, Spain, Belgium, Greece and Italy. The entire city of Venice may get submerged (Anonymous 2018). In USA, New York City and Miami would be particularly vulnerable.

Crop productivity and human health

Many studies have indicated that climate change is driving increasing losses in crop productivity (Zhu et al. 2021). The models on global yield loss for wheat, maize and rice indicate an increase in yield losses by 10 to 25% per degree Celsius warming (Deutsch et al. 2018). Bras et al. (2021) reported that heatwave and drought roughly tripled crop losses over the last 50 years, from −2.2% (1964–1990) to −7.3% (1991–2015). Overall, the loss in crop production from climate-driven abiotic stresses may exceed US$ 170 billion year^{-1} and represents a major threat to global food security (Razaaq et al. 2021). Analysis of annual field trials of common wheat in California from 1985 to 2019 (35 years), during which the global atmospheric CO_2 concentration increased by 19%, revealed that the yield declined by 13% (Bloom and Plant 2021). Apart from crop yield, climate change is reported to result in the decline of nutritional value of food grains (Jagermeyr et al. 2021). For example, rising atmospheric CO_2 concentration reduces the amounts of proteins, minerals and vitamins in rice (Zhu et al. 2018). This may be true in other cereal crops also. As rice supplies 25% of all global calories, this would greatly affect the food and nutritional security of predominantly rice growing countries. Climate change would also increase

the prevalence of insect pests adding to the yield loss of crops. The prevailing floods and droughts also affect food production significantly. Global warming also affects crop productivity through its impact on pollinators. Insect pollinators contribute to crop production in 75% of the leading food crops (Rader et al. 2013). Climate change contributes significantly to the decline in density and diversity of pollinators (Shivanna 2020; Shivanna et al. 2020). Under high as well as low temperatures, bees spend less time in foraging (Heinrich 1979) adding additional constraints to pollination efficiency of crop species.

The IPCC Third Assessment Report (Climate change 2001: The scientific basis – IPCC) concluded that the poorest countries would be hardest hit with reductions in crop yields in most tropical and sub-tropical regions due to increased temperature, decreased water availability and new or changed insect pest incidence. Rising ocean temperatures and ocean acidification affect marine ecosystems. Loss of fish habitats is modifying the distribution and productivity of both marine and freshwater species thus affecting the sustainability of fisheries and populations dependent on them (Salvatteci 2022).

Air pollution is considered as the major environmental risk of climate change due to its impact on public health causing increasing morbidity and mortality (Manisalidis 2020). Particulate matter, carbon monoxide, nitrogen oxide, and sulphur dioxide are the major air pollutants. They cause respiratory problems such as asthma and bronchiolitis and lung cancer. Recent studies have indicated that exposure to air pollution is linked to methylation of immunoregulatory genes, altered immune cell profiles and increased blood pressure in children (Prunicki et al. 2021). In another study wildfire smoke has been reported to be more harmful to humans than automobiles emissions (Aquilera et al. 2021). Stubble burning (intentional incineration of stubbles by farmers after crop harvest) has been a common practice in some parts of South Asia particularly in India; it releases large amount of toxic gases such as carbon monoxide and methane and causes serious damage to the environment and health (Abdurrahman et al. 2020). It also affects soil fertility by destroying the nutrients and microbes of the soil. Attempts are being made to use alternative methods to prevent this practice.

A number of diseases such as zika fever, dengue and chikungunya are transmitted by *Aedes* mosquitoes and are now largely restricted to the monsoon season. Global warming facilitates their spread in time and space thus exposing new populations and regions for extended period to these diseases. Lyme disease caused by a bacterium is transmitted through the bite of the infected blacklegged ticks. It is one of the most common disease in the US. The cases of Lyme disease have tripled in the past two decades. Recent studies have suggested that variable winter conditions due to climate change could increase tick's activity thus increasing the infections (see Pennisi 2022).

Biodiversity

Biodiversity and associated ecoservices are the basic requirements for human livelihood and for maintenance of ecological balance in Nature. Documentation of biodiversity, and its accelerating loss and urgent need for its conservation have become the main concern for humanity since several decades (Wilson and Peter 1988; Wilson 2016; Heywood 2017; IPBES 2019; Genes and Dirzo 2021; Shivanna and Sanjappa 2021). It is difficult to analyse the loss of biodiversity exclusively due to climate change as other human-induced environmental changes such as habitat loss and degradation, overexploitation of bioresources and introduction of alien species also interact with climate change and affect biodiversity and ecosystems. In recent decades there has been a massive loss of biodiversity leading to initiation of the sixth mass extinction crisis due to human-induced environmental changes. These details are not discussed here; they are dealt in detail in many other reviews (Leech and Crick 2007; Sodhi and Ehrlich 2010; Lenzen et al. 2012; Dirzo and Raven 2003; Raven 2020; Ceballos et al. 2015; Beckman et al. 2020; Shivanna 2020; Negrutiu et al. 2020; Soroye et al. 2020; Wagner 2020, 2021; Anonymous 2021; Zattara and Aizen 2021).

Terrestrial species

There are several effects on biodiversity caused largely by climate change. Maxwell et al. (2019) reviewed 519 studies on ecological responses to extreme climate events (cyclones, droughts, floods, cold waves and heat waves) between 1941 and 2015 covering amphibians, birds, fish, invertebrates, mammals, reptiles and plants. Negative ecological responses have been reported for 57% of all documented groups including 31 cases of local extirpations and 25% of population decline.

Increase in temperature impacts two aspects of growth and development in plants and animals. One of them is a shift in distributional range of species and the other is the shift in phenological events. Plant and animal species have adapted to their native habitat over 1000s of years. As the temperature gets warmer in their native habitat, species tend to move to higher altitudes and towards the poles in search of suitable temperature and other environmental conditions. There are a number of reports on climate change-induced shifts in the distributional range of both plant and animal species (Grabherr et al. 1994; Cleland et al. 2007; Parmesan and Yohe 2003; Beckage et al. 2008; Pimm 2009; Miller-Rushing et al. 2010; Lovejoy and Hannah 2005; Lobell et al. 2011). Many species may not be able to keep pace with the

changing weather conditions and thus lag behind leading to their eventual extinction. Long-term observations extending for over 100 years have shown that many species of bumblebees in North-America and Europe are not keeping up with the changing climate and are disappearing from the southern portions of their range (Kerr et al. 2015). Most of the flowering plants depend on animals for seed dispersal (Beckman et al. 2020). Defaunation induced by climate change and other environmental disturbances has reduced long-distance seed dispersal. Prediction of dispersal function for fleshly-fruited species has already reduced the capacity of plants to track climate change by 60%, thus severely affecting their range shifts (Fricke et al. 2022).

Climate change induced shifts in species would threaten their sustenance even in protected areas as they hold a large number of species with small distributional range (Velasquez-Tibata et al. 2013). Pautasso (2012) has highlighted the sensitivity of European birds to the impacts of climate change in their phenology (breeding time), migration patterns, species distribution and abundance. *Metasequoia glyptostroboides* is one of the critically endangered species with extremely small populations distributed in South-Central China. Zhao et al. (2020) analysed detailed meteorological and phenological data from 1960 to 2016 and confirmed that climate warming has altered the phenology and compressed the climatically suitable habitat of this species. Their studies revealed that the temperature during the last 57 years has increased significantly with the expansion of the length of growing season of this species. Climatically suitable area of the species has contracted at the rate of 370.8 km^2 per decade and the lower and upper elevation limits shrunk by 27 m over the last 57 years.

The other impact of climate change on plant and animal species has been in their phenological shift. Phenology is the timing of recurring seasonal events; it is a sort of Nature's calendar for plants and animals. In flowering plants, various reproductive events such as the timing of flowering, fruiting, their intensity, and longevity are important phenological events, and in animals some of the phenological events include building of nests in birds, migration of animal species, timing of egg laying and development of the larva, pupa and adult in insects. Phenological events of both plants and animals are generally fixed in specific time of the year as they are based on environmental cues such as temperature, light, precipitation and snow melt. Phenological timings of species are the results of adaptations over 100 s of years to the prevailing environment. Wherever there is a mutualism between plants and animals, there is a synchrony between the two partners. For example in flowering plants, flowering is associated with the availability of pollinators and fruiting is associated with the availability of seed dispersers and optimal conditions for seed germination and seedling establishment. In animals also, phenological events are adapted to

suit normal growth and reproduction. In temperate regions, melting of ice initiates leafing in plants; this is followed by the flowering in the spring. Similarly, warming of the climate before the spring induces hatching of the hibernating insects which feed on newly developed foliage. Insects emerge and ready to pollinate the flowers by the time the plants bloom.

The dates of celebration of the cherry blossom festival, an important cultural event in Japan that coincides with the peak of flowering period of this species and for which > 1000 years of historical records are available, has shown advances in the dates of the festival in recent decades (Primack et al. 2009). The records between 1971 and 2000 showed that the trees flowered an average of 7 days earlier than all the earlier years (Allen et al. 2013). These advances were correlated with increasing temperature over the years. Spring temperatures in the Red River valley, North Dakota, USA have extended the period of the growing season of plants significantly over the years. Flowering times, for which data are available from 1910 to 1961, have been shown to be sensitive to at least one variable related to temperature or precipitation for 75% of the 178 species investigated (Dunnell and Traverse 2011). The first flowering time has been significantly shifted earlier or later over the last 4 years of their study in 5–15% of the observed species relative to the previous century. *Rhododendron arboretum*, one of the central Himalayan tree species, flowers from early February to mid-March. Generalized additive model using real-time field observations (2009–2011) and herbarium records (1893–2003) indicated 88–97 days of early flowering in this species over the last 100 years (Gaira et al. 2014). This early flowering was correlated with an increase in the temperature.

One of the consequences of a shift in the distributional range of species and phenological timings is the possible uncoupling of synchronization between the time of flowering of plant species and availability of its pollinators (see Gerard et al. 2020). When a plant species migrates, its pollinator may not be able to migrate; similarly when a pollinator migrates, the plant species on which it depends for sustenance may not migrate. Memmott et al. (2007) explored potential disruption of pollination services due to climate change using a network of 1420 pollinators and 429 plant species by simulating consequences of phenological shifts that can be expected with doubling of atmospheric CO_2. They reported phenological shifts which reduced available floral resources to 17–50% of all pollinator species. A long-term study since the mid-1970s in the Mediterranean Basin has indicated that unlike the synchrony present in the earlier decades between the flowering of plant species and their pollinators, insect phenoevents during the last decade showed a steeper advance than those of plants (Gordo and Sanz 2005). Similar asynchrony has been reported between the flowering of *Lathyrus* and one of its pollinators, *Hoplitis fulgida*

(Forrest and Thomson 2011). Asynchrony between flowering and appearance of pollinator has also been reported in a few other cases (Kudo and Ida 2013; Kudo 2014). Such asynchrony could affect the sustenance of plant and/or pollinator species in the new environment.

Marine species

Amongst the marine species, corals are the most affected groups due to the rise in temperature and acidity of oceans. Corals live in a symbiotic relationship with algae which provide colour and photosynthates to the corals. Corals are extremely sensitive to heat and acidity; even an increase of 2–3°F of ocean water above normal results in expulsion of the symbiotic algae from their tissues leading to their bleaching (Hoegh-Guldberg et al. 2017). When this bleached condition continues for several weeks, corals die. Nearly one-third of the Great Barrier Reef, the world's largest coral reef system that sustains huge Australian tourism industry, has died as a result of global warming (Hughes et al. 2018). According to the experts the reef will be unrecognizable in another 50 years if greenhouse gas emissions continue at the current rate.

According to UNESCO, coral reefs in all 29 reef-containing World Heritage sites would cease to exist as functioning ecosystems by the end of this century if greenhouse gas emissions continue to be emitted at the present rate (Elena et al. 2020). Recent assessment of the risk of ecosystem collapse to coral reefs of the Western Indian Ocean, covering about 5% of the global total, range from critically endangered to vulnerable (Obura et al. 2021). Coral reefs provide suitable habitat for thousands of other species, including sharks, turtles and whales. If corals die, the whole ecosystem will get disrupted.

Melting of ice in Arctic region due to global warming is threatening the survival of native animals such as polar bear, Arctic fox and Arctic wolf. Rising of sea level also leads to the extinction of a large number of endangered and endemic plant and animal species in submerged coastal areas and islands. Over 180,000 islands around the globe contain 20% of the world's biodiversity. Bellard et al. (2013) assessed consequences of sea level rise of 1–6 m for 10 insular biodiversity hotspots and their endemic species at the risk of potential extinction. Their study revealed that 6 to19% of the 4447 islands would be entirely submerged depending on the rise of sea level; three of them, the Caribbean islands, the Philippines and Sundaland, displayed the most significant hotspots representing a potential threat for 300 endemic species. According to the Centre for Biological Diversity (2013) 233 federally protected threatened and endangered species in 23 coastal states are threatened if rising sea is unchecked. Recently more than 100 Aquatic Science Societies representing over 80,000 scientists from seven continents sounded climate alarm (Bonar 2021). They have highlighted the effects of climate change on marine and aquatic ecosystems and have called on the world leaders and public to undertake mitigation measures to protect and sustain aquatic systems and theirs services.

Mitigation measures

The principal mitigation measures against climate change are obvious; they include significant reduction in greenhouse gas emission, prevention of deforestation and increase in the forest cover. To reduce greenhouse gas emission, use of coal and fossil fuels needs to be reduced markedly. As climate change is a global challenge, local solutions confined to one or a few countries do not work; we need global efforts. Many attempts are being made to achieve these objectives at the global level since many decades. Mitigation measures are largely at the level of diplomatic negotiations involving states and international organizations, Governments and some nongovernmental organizations. The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. Its mandate was to provide political leaders with periodic scientific assessments concerning climate change, its implications and risks, and also to put forward adaptation and mitigation strategies. In 1992 more than 1700 World scientists, including the majority of living Nobel laureates gave the first Warning to Humanity about climate change and associated problems. They expressed concern about potential damage to the Planet Earth by human-induced environmental changes such as climate change, continued human population growth, forest loss, biodiversity loss and ozone depletion. Conference of Parties (COP) of the UN Convention on Climate Change was established in 1992 under the United Nations Framework Convention on Climate Change (UNFCCC) to discuss global response to climate change. Its first meeting (COP 1) was held in Berlin in March 1995 and is being held every year since then. The Fifth Assessment Report of the IPCC, released in November 2014, projected an increase in the mean global temperature of 3.7 to 4.8 °C by 2100, relative to preindustrial levels (1850), in the absence of new policies to mitigate climate change; it highlighted that such an increase would have serious consequences. This prediction compelled the participating countries at the COP 21 held in Paris in December 2015 to negotiate effective ways and means of reducing carbon emissions. In this meeting the goal to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to preindustrial levels was adapted by 196 participating countries as a legally binding treaty on climate change. It also mandated review of progress every 5 years and the development of a fund containing $100

billion by 2020, which would be replenished annually, to help developing countries to adopt non-greenhouse-gas-producing technologies.

In 2017, after 25 years after the first warning, 15,354 world scientists from 184 countries gave 'second warning to humanity' (Ripple et al. 2017). They emphasized that with the exception of stabilizing the stratospheric ozone layer, humanity has failed to make sufficient progress in solving these environmental challenges, and alarmingly, most of them are getting far worse. Analysis of Warren et al. (2018) on a global scale on the effects of climate change on the distribution of insects, vertebrates and plants indicated that even with 2 °C temperature increase, approximately 18% of insects, 16% of plants and 8% of vertebrates species are projected to loose > 50% geographic range; this falls to 6% for insects, 8% for plants and 4% for vertebrates when temperature increase is reduced to 1.5 °C.

UN Report on climate change (prepared by > 90 authors from 40 countries after examining 6000 scientific publications) released in October 2018 in South Korea also gave serious warning to the world. Some of the salient features of this report were:

- Overshooting 1.5 °C will be disastrous. It will have devastating effects on ecosystems, communities and economies. By 2040 there could be global food shortages, the inundation of coastal cities and a refugee crisis unlike the world has ever seen.
- Even 1.5 °C warming would rise sea levels by 26–77 cm by 2100; 2 °C would add another 10 cm which would affect another 10 million people living in coastal regions.
- Coral reefs are projected to decline 70–90% even at 1.5 °C. At 2 °C, 99% of the reefs would be ravaged.
- Storms, floods, droughts and forest fires would increase in intensity and frequency.
- The world has already warmed by about 1 °C since preindustrial times. We are currently heading for about 3–4 °C of warming by 2100.
- Unless rapid and deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades, achieving the goals of the 2015 Paris Agreement will be beyond reach.
- To keep 1.5 °C target, coal's share of global electricity generation must be cut from the present 37% to no more than 2% by 2050. Renewable power must be greatly expanded. Net CO_2 emissions must come down by 45% (from 2010 levels) by 2030 and reach net zero (emissions of greenhouse gases no more than the amount removed from the atmosphere) around 2050.

This report awakened the world Governments about the seriousness of the climate change. The COP 26 meeting which was to be held in 2020 had to be postponed due to Covid-19 pandemic. The first part of the sixth report of IPCC was released in August 2021 (AR6 Climate Change 2021), just before the postponed COP 26 meeting was to be held; it highlighted that the threshold warming of 1.5 °C (the target of keeping the warming by the end of the century) would reach in the next 20 years itself and if the present trends continue, it would reach 2.7 °C by the end of the century.

Under this predicted climate emergency (see Ripple et al. 2020), COP 26 meeting was held in Glasgow, Scotland between October 31 and November 12, 2021. Nearly 200 countries participated in this meeting. The main aim of the COP 26 was finalization of the rules and procedures for implementation of the Paris agreement to keep the temperature increase to 1.5 °C. A number of countries including USA and European Union pledged to reach net zero carbon emission by 2050. China pledged to reach net zero emissions by 2060 and India by 2070. India also committed to reduce the use of fossil fuels by 40% by 2030. More than 100 countries committed to reduce worldwide methane emissions by 30% (of 2020 levels) by 2030 and to end deforestation by 2030. The average atmospheric concentration of methane reached a record 1900 ppb in September 2021; it was 1638 ppb in 1983 (US National Oceanic and Atmospheric Administration), highlighting the importance of acting on pledges made at the COP 26.

One of the limitations of COP meetings has been nonadherence of the commitment made by developed countries at Paris meeting to transfer US $100 billion annually to developing and poor countries to support climate mitigation and loss of damage, through 2025; only Germany, Norway and Sweden are paying their share. Several experts feel that the adoption of the Glasgow Climate Pact was weaker than expected. According to the assessment of Climate Action Tracker, a non-profit independent global analysis platform, emission reduction commitments by countries still lead to 2.4 °C warming by 2100. However, a positive outcome of the meeting was that it has kept alive the hopes of achieving the 1.5 °C goal by opening the options for further discussion in the coming COP meetings. Apart from implementation of mitigation pledges made by countries, it is also important to pay attention to climate adaptation since the negative effects of climate change will continue for decades or longer (AR6 Climate Change 2021). Investment in early warning is an important means of climate adaptation, which is lacking in many parts of Africa and Latin America.

Conclusions

Climate change has now become the fastest growing global threat to human welfare. The world has realized the responsibility of the present generation as it is considered to be

the last generation capable of taking effective measures to reverse its impact. If it fails, human civilization is likely to be doomed beyond recovery. As emphasized by many organizations, the climate crisis is inherently unfair; poorer countries will suffer its consequences more than others. India is one amongst the nine countries identified to be seriously affected by climate change. According to a WHO analysis (2016) India could face more than 25% of all global climate-related deaths by 2050 due to decreasing food availability. China is expected to face the highest number of per capita food insecurity deaths. Bhutan, a small Himalayan kingdom with 60% forest cover, is the most net negative carbon emission country; its GHG emission is less than the amount removed from the atmosphere. Other countries should aim to emulate Bhutan as early as possible.

A number of other options have been suggested to trap atmospheric carbon dioxide (Climate change mitigation—Wikipedia). Carbon storage through sequestration of organic carbon by deep-rooted grasses has been one such approach (Fisher et al. 1994). Several studies from Africa have indicated that introduction of *Brachiaria* grasses in semi-arid tropics can help to increase not only carbon stock in the soil but also yield greater economic returns (Gichangi et al. 2017). Recently a new seed bank, 'Future Seeds' was dedicated at Palmira, Columbia to store world's largest collection of beans, cassava, and tropical forage grasses for the use of breeders to create better performing and climate-resistant crops (Stokstad 2022). *Brachiaria humidicola* is one of the tropical forage grass stored in this seed bank for its potential benefit in carbon sequestration. Lavania and Lavania (2009) have suggested vetiver (*Vetiveria zizanioides*), a C_4 perennial grass, with massive fibrous root system that can grow up to 3 m into the soil in 1 year, as a potential species for this purpose. Vetiver is estimated to produce 20–30 tonnes of root dry matter per hectare annually and holds the potential of adding 1 kg atmospheric CO_2 annually to the soil carbon pool per m^2 surface area. Carbon dioxide capture and storage is another such potential approach. At present it is too expensive and this approach may have to wait until improvement of the technology, reduction in the cost and feasibility of transfer of the technology to developing countries (IPCC Special Report on carbon dioxide capture and storage 2005).

There has been some discussion on the role of climate change on speciation (Levin 2019; Gao et al. 2020). Some evolutionary biologists have observed that the rate of speciation has accelerated in the recent past due to climate change and would continue to increase in the coming decades (Thomas 2015; Levin 2019; Gao et al. 2020). They propose that auto- and allo-polyploidy are going to be the primary modes of speciation in the next 500 years (Levin 2019, see also Gao 2019, Villa et al. 2022). However, extinction of species imposed by climate change may excel positive impact on plant speciation via polyploidy (Gao et al.

2020). The question is will climate change induce higher level of polyploidy and other genetic changes in crop species also that would promote evolution of new genotypes to sustain productivity and quality of food grains? If so, it would ameliorate, to some extent, food and nutritional insecurity of humans especially in the developing world.

Effective implementation of the pledges made by different countries in COP 26 and actions to be taken in the coming COP meetings are going to be crucial and determine humanity's success or failure in tackling climate change emergency. COP 26 climate pact to cut greenhouse gas emissions, end of deforestation and shift to sustainable transport is certainly more ambitious then earlier COPs. There are also many other positive signals for reducing fossil fuels. Scientists have started using more precise monitoring equipment to collect more reliable environmental data, and more options are being developed by researchers on renewable and alternate energy sources, and to capture carbon from industries or from the air (Chandler D, MIT News 24 Oct 2019, Swain F, BBC Future Planet, 12 March 2021). Scotland has become coal-free and Costa Rica has achieved 99% renewable energy. India has reduced the use of fossil fuel by 40% of it installed capacity, 8 years ahead of its commitment at the COP 26.

Further, people are becoming more conscious to reduce carbon emission by following climate-friendly technologies. Human sufferings associated with an increase in natural disasters throughout the world have focussed public attention on climate change as never before. They also realise the benefits of improved air quality by reducing consumption of coal and fossil fuels on health and ecosystems. The demand for electric vehicles is steadily growing. Reforestation is being carried out in a large scale in many countries. Recent studies across a range of tree plantations and native forests in 53 countries have revealed that carbon storage, soil erosion control, water conservation and biodiversity benefits are delivered better from native forests compared to monoculture tree plantations, although the latter yielded more wood (Hua et al. 2022). This has to be kept in mind in reforestation programmes. Hopefully the world will be able to realize the goal of limiting the temperature rise to 1.5 °C by the end of the century and humanity would learn to live in harmony with Nature.

Declarations

Conflict of interest The author declares no conflict of interest.

References

Abdurrahman, M.I., Chaki, S., Saini, G.: Stubble burning: effects on health & environment, regulations and management practices.

Environ. Adv. (2020). https://doi.org/10.1016/j.envadv.2020.100011

Allen, J.M., Terres, M.A., Katsuki, T., et al.: Modelling daily flowering probabilities: expected impact of climate change on Japanese cherry phenology. Global Change Biol. **20**, 1251–1263 (2013). https://doi.org/10.1111/gcb.12364

Anonymous (2018) https://www.euronews.com/2018/02/02/rising-sea-levels-threat-a-shrinking-european-coastline-in-2100

Anonymous (2021) Special Issue. Global decline in the Anthropocene. Proc Natl Acad Sci, USA 118: No 2

Aquilera, R., Curringham, T.W., Gershunov, A., Benmarhnia, T.: Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. Nat. Commun. (2021). https://doi.org/10.1038/s41467-021-21708-0

AR6 Climate Change: The sixth assessment report on climate change. IPCC, Geneva (2021). https://www.ipcc.ch/report/ar6/wg1/

Beckage, B., Osborne, B., Gavin, D.G., et al.: A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. Proc. Natl. Acad. Sci. USA **105**, 4197–4202 (2008). https://doi.org/10.1073/pnas.0708921105

Beckman, N.G., Aslan, C.E., Rogers, H.S.: The role of seed dispersal in plant populations: perspectives and advances in a changing world. AoB Plants (2020). https://doi.org/10.1093/aobpla/plaa010

Bellard, C., Leclerc, C., Courchamp, F.: Impact of sea level rise on the 10 insular biodiversity hotspots. Global Ecol. Biogeogr. (2013). https://doi.org/10.1111/geb.12093

Bloom, A.J., Plant, R.C.: Wheat grain yield decreased over the past 35 years, but protein content did not change. J. Exptl. Bot. **72**, 6811–6821 (2021). https://doi.org/10.1093/jxb/erab343

Bonar, S.A.: More than 111 aquatic-science societies sound climate alarm. Nature **589**, 352 (2021). https://doi.org/10.1038/d41586-021-00107-x

Bras, T.A., Seixas, J., Nuno, C., Jonas, J.: Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environ. Res. Lett. (2021). https://doi.org/10.1088/1748-9326/abf004

Ceballos, G., Ehrlich, P.P., Barnosky, A.D., et al.: Accelerated modern human-induced species losses: Entering the sixth mass extinction. Sci. Adv. **1**, e1400253 (2015). https://doi.org/10.1126/sciadv.1400253

Centre for Biological Diversity: Deadly Waters: How Rising Seas Threaten 233 Endangered Species. (2013) https://www.biologicaldiversity.org/campaigns/sea_level_rise/pdfs/Sea_Level_Rise_Report_2013_web.pdf

Cleland, E.E., Chuine, I., Menzel, A., et al.: Shifting plant phenology in response to global change. Trends Ecol. Evol. **22**, 357–365 (2007). https://doi.org/10.1016/j.tree.2007.04.003

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., et al.: Increase in crop losses to insect pests in a warming climate. Science **361**, 916–919 (2018). https://doi.org/10.1126/science.aat3466

Dirzo, R., Raven, P.H.: Global state of biodiversity and loss. Ann. Rev. Environ. Res. **28**, 137–167 (2003). https://doi.org/10.1146/annurev.energy.28.050302.105532

Dunnell, K.L., Travers, S.E.: Shifts in the flowering phenology of the northern Great Plains: patterns over 100 years. Am. J. Bot. **98**, 935–945 (2011). https://doi.org/10.3732/ajb.1000363

Elena, O., Matthew, E.-S., Matea, O., et al.: IUCN World Heritage Outlook 3. In: A conservation assessment of all natural World Heritage sites. IUCN, Gland (2020)

Fisher, M.J., Rao, I.M., Ayarza, M.A., et al.: Carbon storage by introduced deep-rooted grasses in the South American Savannas. Nature **371**, 236–238 (1994)

Forrest, J.R.K., Thomson, J.D.: An examination of synchrony between insect emergence and flowering in the Rocky Mountain meadows. Ecol. Monogr. **81**, 469–491 (2011)

Fricke, E.C., Ordonez, A., Rogers, H.S., et al.: The effects of defaunation on plants' capacity to track climate change. Science **375**, 210–214 (2022). https://doi.org/10.1126/science.abk3510

Gaira, K.S., Rawal, R., Rawat, B., Bhatt, I.D.: Impact of climate change on the flowering of *Rhododendron arboreum* in central Himalaya, India. Curr. Sci. **106**, 1735–1738 (2014)

Gao, J.G.: Dominant plant speciation types. A commentary on: plant speciation in the age of climate change. Ann. Bot. **124**, iv–vi (2019). https://doi.org/10.1093/aob/mcz174

Gao, J.G., Liu, H., Wang, N., et al.: Plant extinction excels plant speciation in the Anthropocene. BMC Plant Biol. **20**, 430 (2020). https://doi.org/10.1186/s12870-020-02646-3

Genes, L., Dirzo, R.: Restoration of plant–animal interactions in terrestrial ecosystems. Biol. Conserv. (2021). https://doi.org/10.1016/j.biocon.2021.109393

Gerard, M., Vanderplanck, M., Wood, T., Michez, D.: Global warming and plant-pollinator mismatches. Emerg. Top. Life Sci. **4**, 77–86 (2020). https://doi.org/10.1042/ETLS20190139

Getirana, A., Libonati, R., Cataldi, M.: Brazil is in water crisis—it needs a drought plan. Nature **600**, 218–220 (2021). https://doi.org/10.1038/d41586-021-03625-w

Gichangi, E.M., Njarui, D.M.G., Gatheru, M.: Plant shoots and roots biomass of *Brachiaria* grasses and their effect on soil carbon in the semi-arid tropics of Kenya. Trop. Subtrop. Agroecosyst. **20**, 65–74 (2017)

Gordo, O., Sanz, J.J.: Phenology and climate change: a long-term study in a Mediterranean locality. Oecologia **146**, 484–495 (2005). https://doi.org/10.1007/s00442-005-0240-z

Grabherr, G., Gottfried, M., Pauli, H.: Climate effects on mountain plants. Nature **369**, 448 (1994)

Hausfather, Z., Drake, H.F., Abbott, T., Schmidt, G.A.: Evaluating the performance of past climate model projections. Geophys. Res. Lett. (2019). https://doi.org/10.1029/2019GL085378

Heinrich, B.: Keeping a cool head: honeybee thermoregulation. Science **205**, 1269–1271 (1979)

Heywood, V.H.: Plant conservation in the Anthropocene: challenges and future prospects. Plant Divers. **39**, 314–330 (2017). https://doi.org/10.1016/j.pld.2017.10.004

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S.: Coral Reef Ecosystems under climate change and ocean acidification. Front. Mar. Sci. **4**, 158 (2017). https://doi.org/10.3389/fmars.2017.00158

Hua, F., Bruijnzeel, L.A., Meli, P., et al.: The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. Science (2022). https://doi.org/10.1126/science.abl4649

Hughes, T.P., Kerry, T.J., Baird, A.H., et al.: Global warming transforms coral reef assemblages. Nature **556**, 492–496 (2018). https://doi.org/10.1038/s41586-018-0041-2

Immerzeel, W.W., Lutz, A.F., Andrade, M., et al.: Importance and vulnerability of the world's water towers. Nature **577**, 364–369 (2020). https://doi.org/10.1038/s41586-019-1822-y

IPBES: The intergovernmental science-policy platform on biodiversity and ecosystem services. In: Sustainable development goals. IPBES, Bonn (2019)

IPCC: IPCC special report on carbon dioxidecapture and storage (2005). https://www.ipcc.ch›2018/03›srccs_wholereport-1

Indian State Forest Report: Forest Survey of India (2019). https://www.drishtiias.com

Jägermeyr, J., Müller, C., Ruane, A.C., et al.: Climate impacts on global agriculture emerge earlier in new generation of climate

and crop models. Nat. Food (2021). https://doi.org/10.1038/s43016-021-00400-y

Kerr, J.T., Pinder, A., Galpern, P., et al.: Climate impacts on bumblebees coverage across continents. Science **349**, 177–180 (2015). https://doi.org/10.1126/science.aaa7031

King, O., Bhattacharya, A., Ghuffar, S., Tait, A., et al.: Six decades of glacier mass changes around Mt. Everest are revealed by historical and contemporary Images. One Earth (2021). https://doi.org/10.1016/j.oneear.2020.10.019

Kudo, G.: Vulnerability of phenological synchrony between plants and pollinators in an alpine ecosystem. Ecol. Res. **29**, 571–581 (2014). https://doi.org/10.1007/s11284-013-1108-z

Kudo, G., Ida, T.Y.: Early onset of spring increases the mismatch between plants and pollinators. Ecology **94**, 2311–2320 (2013). https://doi.org/10.1890/12-2003.1

Lavania, U.C., Lavania, S.: Sequestration of atmospheric carbon into subsoil horizons through deep-rooted grasses-vetiver grass model. Curr. Sci. **97**, 618–619 (2009)

Lee, E., Carrivick, J.L., Quincey, D.J., et al.: Accelerated mass loss of Himalayan glaciers since the little ice age. Sci. Rep. **11**, 24284 (2021). https://doi.org/10.1038/s41598-021-03805-8

Leech, D.I., Crick, H.Q.P.: Influence of climate change on the abundance, distribution and phenology of woodland bird species in temperate regions. Ibis **149**(Suppl. 2), 128–145 (2007). https://doi.org/10.1111/j.1474-919X.2007.00729.x

Leeming, J.: Meet the food pioneer whose meat replacements are rocking the gravy boat. Nature **590**, 176 (2021). https://doi.org/10.1038/d41586-021-00264-z

Lenzen, M., Moran, D., Kanemoto, K., et al.: International trade drives biodiversity threats in developing nations. Nature **486**, 109–112 (2012). https://doi.org/10.1038/nature11145

Levin, D.A.: Plant speciation in the age of climate change. Ann. Bot. **124**, 769–775 (2019). https://doi.org/10.1093/aob/mcz108

Lobell, D.B., Schlenker, W., Costa-Roberts, J.: Climate trends and global crop production since 1980. Science **333**, 616–620 (2011). https://doi.org/10.1126/science.1204531

Lovejoy, T.E., Hannah, L. (eds.): Biodiversity and climate change: transforming the biosphere. Yale University Press, New Haven, London (2005)

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E.: Environmental and health impacts of air pollution: a review. Front. Public Health (2020). https://doi.org/10.3389/fpubh.2020.00014

Maxwell, S.L., Butt, N., Maron, M., et al.: Conservation implications of ecological responses to extreme weather and climate events. Divers. Distrib. **25**, 613–625 (2019). https://doi.org/10.1111/ddi.12878

McCrystall, M.R., Stroeve, J., Serreze, M., et al.: New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nat. Commun. (2021). https://doi.org/10.1038/s41467-021-27031-y

Memmott, J., Craze, P.E., Waser, N.M., Price, M.V.: Global warming and disruption of plant-pollinator interactions. Ecol. Lett. **10**, 710–717 (2007). https://doi.org/10.1111/j.1461-0248.2007.01061.x

Miller-Rushing, A., Hoye, T.H., Inouye, D., Post, E.: The effects of phenological mismatches on demography. Philos. Trans. R. Soc. B **365**, 3177–3186 (2010). https://doi.org/10.1098/rstb.2010.0148

Negrutiu, I., Frohlich, M.W., Hamant, O.: Flowering plants in the Anthropocene: a political agenda. Trends Plant. Sci. **25**, 349–368 (2020). https://doi.org/10.1016/j.tplants.2019.12.008

Obura, D., Gudka, M., Samoilys, M., et al.: Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. Nat. Sustain. **5**, 104–113 (2021). https://doi.org/10.1038/s41893-021-00817-0

OXFAM International: 5 natural disasters that beg for climate action. (2021) https://www.oxfam.org/en/5-natural-disasters-beg-climate-action

Pacheco, P., Mo, K., Dudley, N., et al.: Deforestation fronts: drivers and responses in a changing world. WWF, Gland (2021)

Parmesan, C., Yohe, G.: A globally coherent fingerprint of climate change impacts across natural systems. Nature **421**, 37–42 (2003). https://doi.org/10.1038/nature01286

Pautasso, M.: Observed impacts of climate change on terrestrial birds in Europe: an overview. Ital. J. Zool. **79**, 296–314 (2012). https://doi.org/10.1080/11250003.2011.627381

Pennisi, E.: Lyme-carrying ticks live longer—and could spread farther—thanks to warmer winters. Science (2022). https://doi.org/10.1126/science.acz9985

Pimentel, D., Pimentel, M.: Sustainability of meat-based and plant-based diets and the environment. Am. J. Clin. Nutr. **78**, 660S-663S (2003). https://doi.org/10.1093/ajcn/78.3.660S

Pimm, S.L.: Climate disruption and biodiversity. Curr. Biol. **19**, R595–R601 (2009). https://doi.org/10.1016/j.cub.2009.05.055

Potapov, P., Turubanova, S., Hansen, M.C., et al.: Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nat. Food (2021). https://doi.org/10.1038/s43016-021-00429-z

Primack, R.B., Higuchi, H., Miller-Rushing, A.J.: The impact of climate change on cherry trees and other species in Japan. Biol. Conserv. **142**, 1943–1949 (2009). https://doi.org/10.1016/j.biocon.2009.03.016

Pruniki, M., Cauwenberghs, N., Lee, J., et al.: Air pollution exposure is linked with methylation of immunoregulatory genes, altered immune cell profiles, and increased blood pressure in children. Sci. Rep. **11**, 4067 (2021). https://doi.org/10.1038/s41598-021-83577-3

Rader, R., Reilly, J., Bartomeus, I., Winfree, R.: Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. Global Change Biol. **19**, 3103–3110 (2013). https://doi.org/10.1111/gcb.12264

Raven, P.H.: Biological extinction and climate change. In: Al-Delaimy, W.K., Ramanathan, V., SánchezSorondo, M. (eds.) Health of people, health of planet and our responsibility, pp. 11–20. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-31125-4_2

Razzaq, A., Wani, S.H., Saleem, F., et al.: Rewilding crops for climate resilience: economic analysis and *de novo* domestication strategies. J Exptl Bot **72**, 6123–6139 (2021). https://doi.org/10.1093/jxb/erab276

Ripple, W.J., Wolf, C., Newsome, T.M., et al.: World scientists' warning to humanity: a second notice. Bioscience **67**, 1026–1028 (2017)

Ripple, W.J., Wolf, C., Newsome, T.M., et al.: World Scientists' warning of a climate emergency. Bioscience **70**, 8–12 (2020). https://doi.org/10.1093/biosci/biz152

Salvatteci, R., Schneider, R.R., Field, E.G.D., et al.: Smaller fish species in a warm and oxygen-poor Humboldt Current system. Science **375**, 101–104 (2022). https://doi.org/10.1126/science.abj0270

Sejiyan, V., Bhatta, R., Malik, P.K., et al.: Livestock as sources of greenhouse gases and its significance to climate change. In: Moya, B.L., Pous, J. (eds.) Greenhouse gases. IntechOpen, London (2016). https://doi.org/10.5772/62135

Shivanna, K.R.: The sixth mass extinction crisis and its impact on biodiversity and human welfare. Resonance **25**, 93–109 (2020)

Shivanna, K.R., Sanjappa, M.: Conservation of endemic and threatened flowering plants: challenges and priorities for India. J. Indian Bot. Soc. **101**, 269–290 (2021)

Shivanna, K.R., Tandon, R., Koul, M.: 'Global pollinator crisis' and its impact on crop productivity and sustenance of biodiversity. In: Tandon, R., Shivanna, K.R., Koul, M. (eds.) Reproductive ecology

of flowering plants: patterns and processes, pp. 395–413. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-4210-716

Sodhi, N.S., Ehrlich, P.R. (eds.): Conservation biology for all. Oxford University Press, Oxford (2010)

Soroye, P., Newworld, T., Kerr, J.: Climate change contributes to widespread declines among bumble bees across continents. Science **367**, 685–688 (2020). https://doi.org/10.1126/science.aax8591

Stokstad, E.: World's largest bean and cassava collection gets a striking new home: "Future Seeds" gene bank will help plant breeders create new varieties of crops and carbon-storing grasses. ScienceInsider (2022). https://doi.org/10.1126/science.abq1510

Thomas, C.D.: Rapid acceleration of plant speciation during the Anthropocene. Trends Ecol. Evol. **30**, 448–455 (2015). https://doi.org/10.1016/j.tree.2015.05.009

Velasquez-Tibata, J., Salaman, P., Catherine, H., Graham, C.H.: Effects of climate change on species distribution, community structure, and conservation of birds in protected areas in Colombia. Reg. Environ. Change **13**, 235–248 (2013). https://doi.org/10.1007/s10113-012-032

Villa, S., Montagna, M., Pierce, S.: Endemism in recently diverged angiosperms is associated with polyploidy. Plant Ecol. (2022). https://doi.org/10.1007/s11258-022-01223-y9-y

Voosen, P.: Key Antarctic ice shelf is within years of failure. Science **374**, 1420–1421 (2021). https://doi.org/10.1126/science.acz9833

Wagner, D.L.: Insect decline in the Anthropocese. Ann. Rev. Entomol. **65**, 457–480 (2020)

Wagner, D.L., Grames, E.M., Forister, M.L. et al.: Insect decline in the Anthropocene: Death by a thousand cuts. Proc. Natl. Acad. Sci. USA **118**, e2023989118 (2021). https://doi.org/10.1073/pnas.2023989118

Warren, R., Price, J., Graham, E., et al.: The projected effect on insects, vertebrates and plants of limiting global warming to 1.5°C rather than 2°C. Science **360**, 791–795 (2018). https://doi.org/10.1126/science.aar3646

WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present. Earth Syst. Sci. Data **10**, 1551–1590 (2018). https://doi.org/10.5194/essd-10-1551-2018

WHO analysis: World Health Statistics 2016. In: Monitoring health for the sustainable development goals. WHO, Geneva (2016)

Wilson, E.O.: Half-earth: our planet's fight for life. Liveright/Norton, New York (2016)

Wilson, E.O., Peter, F.M. (eds.): Biodiversity. National Academy Press, Washington DC (1988)

Zattara, E.E., Aizen, M.A.: Worldwide occurrence of records suggest a global decline in bee species richness. One Earth **4**, 114–123 (2021). https://doi.org/10.1016/j.oneear.2020.12.005

Zhao, Z., Wang, Y., Zang, Z., et al.: Climate warming has changed phenology and compressed the climatically suitable habitat of *Metasequoia Glyptostroboides* over the last half century. Global Ecol. Conserv. **23**, e01140 (2020). https://doi.org/10.1016/j.gecco.2020.e01140

Zhu, C., Kobayashi, K., Loladze, I., et al.: Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci. Adv. **4**, eaaq012 (2018). https://doi.org/10.1126/sciadv.aaq1012

Zhu, T., Flavio, C., De Lima, F., De Smet, I.: The heat is on: how crop growth, development, and yield respond to high temperature. J. Exptl. Bot. **72**, 7359–7373 (2021). https://doi.org/10.1093/jxb/erab308