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# The Impact of Climate Change on Future Biodiversity

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**ABSTRACT:** Many studies in recent years have investigated the effects of climate change on the future of biodiversity. In this review, we first examine the different possible effects of climate change that can operate at individual, population, species, community, ecosystem and biome scales, notably showing that species can respond to climate change challenges by shifting their climatic niche along three non-exclusive axes: time (e.g., phenology), space (e.g., range) and self (e.g., physiology). Then, we present the principal specificities and caveats of the most common approaches used to estimate future biodiversity at global and sub-continental scales and we synthesize their results. Finally, we highlight several challenges for future research both in theoretical and applied realms. Overall, our review shows that current estimates are very variable, depending on the method, taxonomic group, biodiversity loss metrics, spatial scales and time periods considered. Yet, the majority of models indicate alarming consequences for biodiversity, with the worst-case scenarios leading to extinction rates that would qualify as the sixth mass extinction in the history of the earth.

**KEYWORDS:** climate change, future biodiversity, biome, niche, earth, species, community

## I. INTRODUCTION

- Biodiversity is the variety of all life on Earth, including animals, plants and microorganisms.
- Many impacts of climate change – including drought, bushfires, storms, ocean acidification, sea level rise and global warming – affect biodiversity.
- Loss of biodiversity can lead to land degradation, effects on water supply and changes in farming productivity.
- Many plants and animals cannot adapt to the effects of climate change. NSW has 1000 plant and animal species and ecological communities that are at risk of extinction.
- Managing our biodiversity is an important way to prevent further biodiversity loss and extinctions.[1,2,3]
- The importance of biodiversity in NSW
- Biodiversity is the variety of all living organisms on Earth. Diversity can refer to:
  - genetic diversity
  - species diversity – including plants, animals, fungi and microorganisms
  - ecosystem diversity.

Australia is home to more than one million species of plants and animals. Many of these are found nowhere else in the world, including 82% of our mammals and 93% of our frogs.

Biodiversity drives the natural systems that support all life on the planet. This life provides us with clean air and water, food and natural resources. Also, biodiversity increases the ability of ecosystems to do things like:

- hold soils together and maintain soil fertility
- deliver clean water to streams and rivers
- cycle nutrients
- pollinate plants (including crops)
- protect us against pests and diseases.

These are sometimes called 'ecosystem functions' or 'ecosystem services'.

Biodiversity contributes to the beauty and our cultural identity in NSW, and Australia on a whole. Spending time in nature is linked to our health and wellbeing.

How biodiversity is affected by climate change in NSW

Biodiversity is affected by every aspect of climate change including:



- more frequent and intense droughts
- catastrophic bushfires, storms and heatwaves
- sea level rise
- changes in ocean currents and water temperatures
- estuary and ocean acidification.

In the past 200 years, the Australian environment has been modified dramatically. In NSW, 1000 plant and animal species and ecological communities are at risk of extinction

#### Adapting to changes in biodiversity in NSW

In many cases, biodiversity cannot keep up with and adapt to the speed that the environment is changing. Without management intervention, this will lead to local or more widespread extinctions.

To adapt to climate change and preserve biodiversity, we need to have:

- resilient ecosystems, to reduce the stress caused by other human activities such as pollution and land clearing
- interventions for priority species
- identification and protection of places of climate refuges where species are likely to persist
- habitat connectivity to allow species movement
- climate-ready revegetation – planting climate-ready species in revegetation programs.
- the community involved in conservation science-based tools for land management such as Restore and Renew and NSW Niche Finder.

Programs such as the Saving our Species program and NSW National Parks and Wildlife Service are key to protecting our species from climate change. [4,5,6]

Australia's Strategy for Nature 2019–future, and the accompanying Australia's Nature Hub website, is the national biodiversity strategy and action plan.

## **II. DISCUSSION**

Climate change is a pervasive and growing global threat to biodiversity and ecosystems. Here, we present the most up-to-date assessment of climate change impacts on biodiversity, ecosystems, and ecosystem services in the U.S. and implications for natural resource management. We draw from the 4th National Climate Assessment to summarize observed and projected changes to ecosystems and biodiversity, explore linkages to important ecosystem services, and discuss associated challenges and opportunities for natural resource management. We find that species are responding to climate change through changes in morphology and behavior, phenology, and geographic range shifts, and these changes are mediated by plastic and evolutionary responses. Responses by species and populations, combined with direct effects of climate change on ecosystems (including more extreme events), are resulting in widespread changes in productivity, species interactions, vulnerability to biological invasions, and other emergent properties. Collectively, these impacts alter the benefits and services that natural ecosystems can provide to society. Although not all impacts are negative, even positive changes can require costly societal adjustments. Natural resource managers need proactive, flexible adaptation strategies that consider historical and future outlooks to minimize costs over the long term. Many organizations are beginning to explore these approaches, but implementation is not yet prevalent or systematic across the nation.

An organism's response to climate change can be driven by genetic (evolutionary) or non-genetic (plastic) processes (e.g., Franks et al., 2014; Kingsolver and Buckley, 2017). This distinction is important because the mechanism determines the rate of response and whether individuals, populations, and species will be able to keep pace with rapidly changing conditions (Boutin and Lane, 2014). Plastic responses occur within an individual's lifetime and are almost immediate, whereas evolutionary change requires multiple generations (Harrisson et al., 2014; Hendry et al., 2011). Current research is starting to explore the role of epigenetic responses, wherein environmental drivers alter gene expression and can be passed to future generations, occur between generations, and are considered intermediate responses (Jeremias et al., 2018). The distinction between plastic/epigenetic responses and evolutionary change is not always clear, as an organism's ability to respond through these mechanisms can be heritable and subject to evolutionary pressure (Banta and Richards, 2018; Grenier et al., 2016).

Some rapid responses reflect a long history of genetic adaptation to natural variability in climate, and may facilitate persistence during directional climate change by allowing populations to persist long enough for genetic adaptation to occur (Fox et al., 2019; Snell-Rood et al., 2018). While often effective at increasing survival in the short term, some



plastic responses are not beneficial over the long term (Ghalambor et al., 2007): they may entail tradeoffs with fecundity (e.g., smaller body sizes typically produce fewer eggs and more boom/bust population dynamics; Waples and Audzijonyte, 2016), or they may lead to interactions with other species or habitats that ultimately lower survival (Bonamour et al., 2019; Schlaepfer et al., 2002). Negative effects of plastic responses are often delayed and difficult to measure, so tracking long-term demographic responses to ensure populations of concern are truly coping with climate change is important.

The pace of climate change often exceeds average rates of evolutionary change (De Meester et al., 2018). However, evolution can happen in very few generations if populations survive strong selection and favorable genetic variation is already present (Hendry, 2017). Strong selection typically involves high mortality, so populations face extirpation before they can effectively adapt via evolution (Bay et al., 2018). Indeed, recent meta-analyses demonstrate that even species demonstrating adaptive phenotypic responses may be adapting too slowly to keep pace with climate change (Radchuk et al., 2019).

Substantial theoretical and empirical work has focused on predicting and measuring rates of response to climate change in recent years (Bell, 2013; Carlson et al., 2014; Gomulkiewicz et al., 2018; Kopp and Matuszewski, 2014; Pelletier and Coltman, 2018). Rapid trait changes are common and well documented, but most cases are consistent with plastic rather than evolutionary mechanisms (Eastman et al., 2012; Merilä and Hendry, 2014). Although examples do exist of evolutionary responses across multiple taxa (Boutin and Lane, 2014; Charmantier and Gienapp, 2014; Crozier and Hutchings, 2013; Franks et al., 2014), the comparative lack of evidence may be due to complex selection and genetic landscapes, methodological constraints that hinder measurement of genetic change (Merilä, 2012), and altered species interactions which may outpace evolutionary responses (Section 3.2). Evolutionary rates are complicated to predict because selection acts on many traits simultaneously, possibly with opposing costs and benefits in different life stages or habitats (Crozier et al., 2008). However, because responses vary in the extent to which they reduce extinction risk, tracking multiple responses and understanding their limitations is critical for successful resource management.[7,8,9]

### **III. RESULTS**

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<sub>2</sub>, 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.

#### **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 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 radiates 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<sub>2</sub> in trapping heat. Until 2019, the US, UK, European Union, Canada, Australia, Japan and Russia were the major CO<sub>2</sub> producers and were responsible for 61% of world's emissions. Now, China produces the maximum amount of CO<sub>2</sub> (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<sub>2</sub> 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<sub>2</sub> 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 rely 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<sub>2</sub> 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<sub>2</sub> emitted through various processes and the amount absorbed by the plants. Forests are the main sinks of atmospheric CO<sub>2</sub>. 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<sup>2</sup> 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<sup>2</sup>. 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<sup>2</sup>. 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<sub>2</sub> 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.[10,11,12]

#### 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 2021 with 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 in 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<sup>2</sup> 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<sub>2</sub> 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. Sea 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 sea 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)[13,14,15]. 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<sup>-1</sup> and represents a major threat to global food security (Razaq 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<sub>2</sub> 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<sub>2</sub> 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<sup>2</sup> 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 [16,17,18]. 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<sub>2</sub>. 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.[19]

#### **IV. CONCLUSION**

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 to 19% 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 their services.[20]

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6. ^ IPCC AR6 WG1 Technical Summary 2021, p. 67: "Concentrations of CO<sub>2</sub>, methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) have increased to levels unprecedented in at least 800,000 years, and there is high confidence that current CO<sub>2</sub> concentrations have not been experienced for at least 2 million years."
7. ^ IPCC SRCCL 2019, p. 7: "Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature (high confidence). Climate change... contributed to desertification and land degradation in many regions (high confidence)."
8. ^ IPCC SRCCL 2019, p. 45: "Climate change is playing an increasing role in determining wildfire regimes alongside human activity (medium confidence), with future climate variability expected to enhance the risk and severity of wildfires in many biomes such as tropical rainforests (high confidence)."
9. ^ IPCC SROCC 2019, p. 16: "Over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers (very high confidence), reductions in snow cover (high confidence) and Arctic sea ice extent and thickness (very high confidence), and increased permafrost temperature (very high confidence)."
10. ^ IPCC AR6 WG1 Ch11 2021, p. 1517



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12. ^ IPCC SR15 Ch1 2018, p. 64: "Sustained net zero anthropogenic emissions of CO<sub>2</sub> and declining net anthropogenic non-CO<sub>2</sub> radiative forcing over a multi-decade period would halt anthropogenic global warming over that period, although it would not halt sea level rise or many other aspects of climate system adjustment."
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