Suhaib A. Bandh *Editor*

Climate Change

The Social and Scientific Construct

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Understanding Climate Change: Scientific Opinion and Public Perspective

Fayaz A. Malla, Aiman Mushtaq, Suhaib A. Bandh, Irteza Qayoom, Anh Tuan Hoang, and Shahid-e-Murtaza

Abstract Since the late nineteenth century, the earth's average surface temperature has risen by about 1.18 °C, mainly due to increased carbon dioxide emission into the atmosphere and other anthropogenic activities. Most of the warming happened during the last four decades, with the most recent seven years being the warmest. As shown by global observations, climate change is ongoing, and extensive scientific analysis shows that the greenhouse gases released by human activity are its primary causes. Based on well-established data, most climate science and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change agree that climate change occurs primarily due to human-induced causes and therefore affirm this stance. Although natural activities contribute significantly to climate variability, several evidence suggests that human influences have had an increasingly dominant impact on the observed global warming since the mid-twentieth century. It is a crucial problem that threatens to cause significant natural, social, and economic impacts worldwide. So, it becomes imperative to clearly understand the phenomenon to adopt appropriate mitigation measures with good accuracy and precision.

Keywords Climate change · Understanding · Public perspective · Scientific opinion · Climate scientists

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1 Introduction

The term "climate change" refers to a wide range of physical phenomena as well as a public policy concern and is often used interchangeably with the term "global warming" (Weber and Stern 2011). Scientists now know that various factors, including solar radiation, the earth's orbit around the Sun, seismic activity, ocean tides, and tectonic flats, contribute to long-term climate change on Earth (Leiserowitz and Anthony 2007; Britt 2007). With a method of collective learning that relies on combining observational data and creating hypotheses and trends in evidence synthesis that have been used for 150 years, the scientific understanding of climate change has progressed significantly (National Research Council 2010).

The Intergovernmental Panel on Climate Change (IPCC) publishes a report on the state of climate change science every six to seven years (Cook 2019). (IPCC). Since the Second Review Report (Houghton et al. 1996), their reports on the human contribution to current global warming have developed dramatically from a noticeable human influence on global climate change to the dominant cause of observed warming since the mid-twentieth century in the fifth review report. Various other experiments have also been carried out to determine the degree of agreement among climate scientists about human-induced global warming and reinforce the IPCC's scientific consensus report. Several surveys have reached a consensus of 97%, with 90–100% experimental evidences suggesting that humans are the primary source of global warming.

2 Scientific Consensus on Climate Change

There is considerable scientific consensus that climate change is occurring mostly as a result of human activity. The Intergovernmental Panel on Climate Change (IPCC), a research organisation charged with reviewing the status of climate science to advise policymaking (IPCC 2005), established in 1995 that "the majority of evidence" favoured humans influencing the global climate (Houghton et al. 1995; Oreskes 2010). The Fourth Assessment Report (AR4) of IPCC claimed that there is unambiguous warming and stated that it is difficult to account for the global climate changes of the past 50 years without including the human activities (Alley et al. 2007; Oreskes 2010). Recently, IPCC's Fifth Assessment Report (AR5) published in 2013, updated its report and stated that it is "extremely likely" that human activities are causing climate change (IPCC 2013a, b). This IPCC report is supported by many leading scientific organisations and scientists globally. It is also supported by many comprehensive reviews of the peer-reviewed literature on climate change and expert surveys (van der Linden et al. 2015). However, a minority of scientists deny the consensus position of anthropogenic climate change, and they label themselves as "sceptics" (Dunlap 2013; Leiserowitz et al. 2012). This has created a divergence between public perception and the actual scientific consensus (Cook et al.

2013), which has decreased the public support for climate adaptation and mitigation policies (Aklin and Urpelainen 2014; Ding et al. 2011; McCright et al. 2013; van der Linden et al. 2014). Recent studies have also confirmed that 97–98% of climate scientists affirm the presence of anthropogenic climate change (Anderegg et al. 2010; Cook et al. 2013; Doran and Zimmerman 2009; Oreskes 2004) with some estimates as high as 100% (Powell 2019). Since the 1990s, several studies have been carried out to assess the level of agreement on anthropogenic global warming within the scientific community (Bray 2010; Cook et al. 2016) by using different methodologies, like, surveying members of the relevant scientific community, analysing peer-reviewed climate research, compiling public statements by scientists and mathematical analysis of citation (Cook et al. 2016). Naomi Oreskes conducted a qualitative analysis of the abstracts of 928 articles published in peer-reviewed scientific journals between 1993 and 2003 (Powell 2019) and concluded that 75% of the articles explicitly or implicitly accepted the consensus view; 25% dealt with methods or paleoclimate and took no position on current anthropogenic climate change; and there was no paper that disagreed with the consensus position on Anthropogenic Global Warming (Oreskes 2004). Cook et al. (2013) conducted a review of 11,944 peer-reviewed articles published between 1991 and 2011 using the keywords "global climate change" and "global warming" and found that 97.1% of scientists endorsed the consensus position on Anthropogenic global warming (Cook et al. 2013, 2016), which is consistent with previous surveys of the scientific literature on human-caused climate change (Anderegg et al. 2010; Doran and Zimmerman 2009; Oreskes 2004). In addition to the abstract analysis of papers, the self-rating of authors was also conducted, which additionally established an increase in the scientific consensus on anthropogenic global warming from 1991 to 2011. Powell (2019) recently found that the consensus has reached 100% after analysing 11,602 peer-reviewed publications published in the first seven months of 2019. Though many attempts and approaches have been used by different scientists in estimating the extent to which scientists agree on climate change caused by humans, including analysis of peer-reviewed literature and survey of experts, various studies endorse the man-induced nature of Climate change.

3 Opinion of Leading Scientific Organisations on Climate Change

In contemporary times, the dynamic climate regime of the earth is unquestionably far from normal. The global dimension of this subject demands to be governed at an international platform having legislated authority to stir the issue at a global scale. International environmental conventions, international bodies, multilateral environmental negotiations, and environmental non-governmental organisations constitute what is referred to as the "world environmental regime" (Meyer et al. 1997). Intergovernmental Panel on Climate Change was specifically structured in

1988 to deal with climate change by "assessing the influence of greenhouse gas emissions on climate change, as well as its potential effect on societies" and devise "realistic response strategies for the management of the climate change issue" (IPCC 1990). According to IPCC's AR5, the global average surface temperature would increase between 0.3 and 4.8 °C by 2100 (IPCC 2013a, b). Global climate change, according to the American Anthropological Association, exacerbates underlying socioeconomic problems, causes relocation, destabilises governments, and accelerates epidemic transmissions (Shaffer 2017). United Nations Framework Convention on Climate Change (UNFCCC) unanimously predicted that 2° warming of our planet would have dire consequences (Wittneben et al. 2012). A major share of anthropogenic GHG emissions is contributed by methane (44%), followed by N_2O (29%) and CO_2 (27%) (Gerber et al. 2013). Over the years, the Global Warming Potential (GWP) of CH_4, N_2O, and CO_2 calculated by IPCC and UNFCCC show considerable variations. The latest assessments reveal higher GWP than previous estimates over a 100-year time horizon. FAO statistics for 2001–2003 reveal that annual global CO_2 emissions in the meat transportation sector amounted to about 800–850 thousand tonnes (Steinfeld et al. 2006). Anthropogenic activities have contributed 500 billion tons of carbon in the last 250 years, and at present, with accelerated emission rates, the next 500 billion tons would be added in just 30 years (trillionthton.org 2012). As per UNFCCC, energy consumption and emissions generated by developing countries treading the path of development are bound to increase (Preamble, FCCC). Climate change poses significant and intensifying risks on the basic determinants of health, like access to safe and potable water, adequate sanitation, food security and housing, healthy occupational and environmental conditions (WHO 2008), infrastructure, agriculture and natural ecosystems (IPCC 2014). It has been established that climate change would result in cataclysmic weather episodes at increased frequency and duration through the twenty-first century, negatively impacting human life in numerous ways (IPCC 2014). Intense heatwaves, droughts, severe floods, aggravated tropical cyclone activity, altered precipitation patterns can disrupt water availability, food security, damage infrastructure (Hestres 2015; IPCC 2007a, b; Wittneben et al. 2012), potentially exhausting a significant portion of economic resources. Incidences of malaria and other infectious diseases would also escalate due to the swelling of the vector population at warmer temperatures (Perkins et al. 2018; Rajamani 2010). Although the extent to which these hazards would occur is uncertain (IPCC 2007a, b), it would particularly be problematic for small island nations and technologically backward countries but generally felt across the globe (Adger et al. 2006). IPCC has predicted a temperature increase of 0.5–1 °C in the presence of extreme mitigation measures and 3–6 °C in the worst-case scenario (IPCC 2001a, b, 2007a, b). Studies indicate that in Latin American countries, these changes would deplete plant genetic resources, accelerate desertification, lead to salinisation of agricultural lands (high confidence), and decrease the rice yields by 2020s (medium confidence) (IPCC 2007a, b; Laderach et al. 2011). The after-effects of extreme weather activity are the principal reasons that amplify an area's socioeconomic and environmental vulnerability (Adger 1999). Geographically, there could be a shift in the vulnerability of different areas and a re-localisation of epicentres responsible for food security as an outcome of various climatic and non-climatic threats (FAO 2008). The harmful consequences of climate change are particularly severe in countries where rain-fed agriculture is the principal source of food and wealth (FAO 2008).

Among the human population, children are most susceptible to the negative impacts of climate change (WHO 2018) as their physiological defence systems are still developing. They are also more vulnerable to food scarcity, economic breakdown, and migrationthe indirect effects of climate change (Akresh 2016). UNICEF forecasts that the most severe effects of climate change will be felt in low- to middle-income nations with an 85% worldwide kid population (UNICEF 2014). '*Unless We Act Now*, the report published by UNICEF, details the impact of climate change on children, particularly the most vulnerable (UNICEF 2015).

The Fifth Assessment Report (AR5) of the IPCC states that a temperature increase of 2–3 °C above pre-industrial levels could result in the bio-diversity loss of 20–30% plant and animal species (IPCC 2014), thus establishing climate change as one of the direct drivers of bio-diversity loss (UNEP 2012). A significant portion of youth acknowledges the negative consequences of climate change (Tranter and Skrbis 2014) and are concerned about the manifestation of its impact in their own lives (UNICEF UK 2013). The global perspective regarding climate change was also echoed in the 2015 Paris Agreement. It is "an urgent and potentially irreversible threat to human societies and the planet" (Sanson and Burke 2020). For addressing climate change, policies are conceptualised around mitigation and adaptation strategies (IPCC 2007a, b). These two can become highly effective if incorporated into national and regional plans (FAO 2009b). Climate change is a problematic subject owing to the stakeholders' competing interests.

Currently, stabilising greenhouse gas concentrations in the atmosphere is the priority of environmental organisations to prevent serious disturbances in the climate system due to anthropogenic activities (UNFCCC, Art.2 (Rajamani 2010)). The world leaders decided at the CoP-16 (Mexico) to "reduce emissions and provide funding for adaptation (to climate change) in underdeveloped nations". There have been heated arguments on sharing the burden for mitigating GHG emissions under UNFCCC (Paavola 2005). The Paris Agreement under the aegis of UNFCCC emphasised the induction of non-state members to utilise their capabilities in combating climate change and decentralising climate governance (Jordan et al. 2015). For example, Greenpeace USA strongly opposed the Waxman-Markey bill (the American Clean Energy and Security Act) for inadequately equipped and favouring fossil fuel companies (Pooley 2010). Under its 'Beyond Coal Campaign, Sierra Club focuses on replacing about one-third of the U.S. coal power plants with renewable energy alternatives and opposes coal extraction in Appalachia and Wyoming's Powder River Basin (sierraclub.org, n.d.). Paris Agreement (2016) was the first practical global commitment against climate change where each country worked out its plan for important reductions in the carbon intensity of its GDP by 2030. It aims to curb the global temperature upsurge strictly below 2 °C and preferably within 1.5 °C compared to the pre-industrial levels (U.N. 2015). Being at the greatest risk of climate change impacts, small island states have resolved to restrict the GHG concentrations under 350 ppm CO_2 eq and cut down CO_2 emissions by more than 85% by 2050 (AOSIS 2010). The drastic reductions in the emission of GHGs as proposed by different countries revolves around decarbonising the energy sector and promoting renewable energy sources (Perkins et al. 2018), significant alterations in socio-political establishments, restructuring the economic systems, technological systems, organisational reforms, and the organising systems (den Elzen et al. 2009; IPCC 2007a, b). The current climate change trends demand our swiftly switching over to cleaner energy alternatives while simultaneously making efforts to bring down GHG concentrations in the atmosphere, without which a temperature increase of 4.8 °C is expected in the current century (IPCC 2014).

4 The Public Perspective of Climate Change

Gallup polls done in 2007 and 2008 in 127 countries found that almost a third of the world's population has never heard of global warming. The percentage of people who claimed knowing something substantial about global warming ranged between 15% in Liberia to 95% in Japan. The median number of people reporting awareness of global warming in these 127 countries was 62%. Global warming public perception tends are reported to be higher in developed economies and lower in developing economies. Almost everyone surveyed in Japan and Finland reported awareness of global warming. However, less than a quarter of respondents in African countries such as Liberia and Benin know about global warming and climate change. in India about 35% population has reported awareness of climate change (Pelham and Brett 2009). In most countries surveyed, climate change is seen as a significant threat. People in Greece are worried, with 90% of them marking climate change as a substantial danger. South Korea, France, Spain, and Mexico all have deep opinions on climate change. Americans are less concerned with climate change, with 59% believing it as a significant threat. The least likely to consider climate change poses a substantial danger to their country are those in Russia (43%), Nigeria (41%), and Israel (38%) (Poushter and Huang 2019).

According to a survey conducted by Leiserowitz (2013), public awareness of some serious facets of climate change has increased since the late 1990s, but the United States' concerns about climate change remain mild, as evidenced by the belief that future improvements will be more global in scope but not necessarily local. Despite some scepticism, the poll showed that most Americans believe in global warming (Seymour 2008). While 71% of Americans believe in global warming, just 48% feel there is scientific consensus on why it occurs, and 40% say there is a significant dispute on the matter (Leiserowitz 2007).

5 Climate Change as Seen Through the Lens of the Earth's Energy Flows

Since the dawn of industrialization, human actions have been the primary cause of climate change (IPCC 2013a, b). Growing CO_2 from the fossil fuel burning dominates the growth of greenhouse gases (Trenberth 2020), which can trap the outgoing longwave infrared radiations from the surface of earth and atmosphere. Hence, with the increasing concentration of GHGs, Earth's atmosphere warms until the outgoing longwave radiations increase to match the absorbed solar radiations.

Earth's weather and climate are determined by the amount of energy received from the Sun. Its energy budget explains that the climate is in equilibrium and doesn't depend on incoming and outgoing radiations; rather, it depends on the interaction of incoming energy with the earth through scattering, reflection, absorption, and transformation into other forms of energy. In the earth's climate system, energy could be transformed, transported, and processed through several pathways, with most of the research suggesting that 30% of solar energy is reflected. In comparison, the remaining 70% is converted and transformed into different other forms. Sun is the sole energy source for Earth (Fig. 1), making the solar flow the most dominant energy flow on earth. Around 1.74×10^5 TW of power (equivalent to 4 million tons of oil) is received every second by the earth. Although it is a small portion of the Sun's total power output of 4.1×10^{14} TW in all directions, still the amount is enormous (International Energy Agency 2020). The other forms of energy such as nuclear, geothermal, and tidal also contribute to the total energy budget of the earth. Even though these energies contribute less, they are critical in ensuring the energy balance of the earth. Around 1 TW of nuclear fuels is used, which doesn't originate from the Sun, and about 44 TW is harvested from geothermal sources. Likewise, around 3TW energy comes from tidal forces acting between the Earth and Moon (Fig. 2).

Under balanced conditions, the atmosphere may be thought of as the average energy path that incoming solar radiations travel to maintain the system's overall energy balance. This energy balance and these average energy routes adjust in

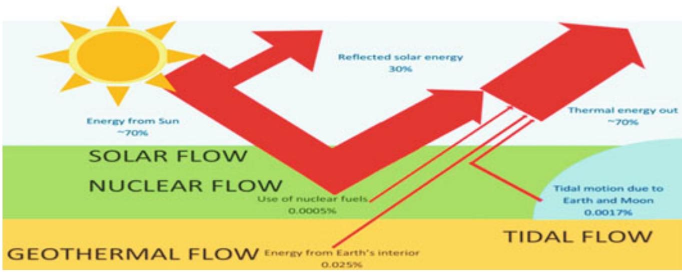

Fig. 1 Energy flows on the earth

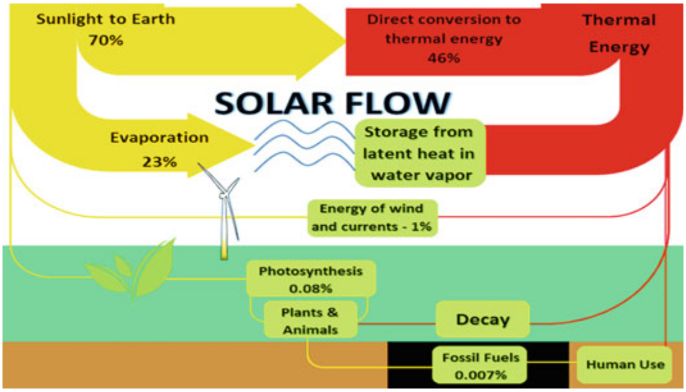

Fig. 2 Specific pathways within the dominant solar flow

response to external radiative forces and internal redistribution that ultimately determines the future climate change. Climate model simulations over multiple centuries show that the system generates its variability while in equilibrium. Internal variability is dominated by weather systems and the irregular character of air circulations on a daily or weekly time frame. It has been found that internal variability correlates with long-term patterns in the oceans and atmosphere, such as the North Atlantic Oscillations (NAO) (Herrell et al. 2002), El-Nino Southern Oscillation (El-Nino Southern Oscillation) (Mcphaden et al. 2006), and Atlantic Oscillation (Atlantic Oscillation) (Connolley 1997; Knight et al. 2005). These forms of heterogeneity transfer energy within the ocean and among the other components of the climate system. The climate system's internal "noise" is an essential concept in understanding climate change experienced or simulated. In simplest terms, climate change happens when an external force disturbs the climate equilibrium (Palmer 2012).

Solar irradiance in general, natural or man-made aerosols, and ambient greenhouse gass all contribute to the climate system's "external forcing". The relative relevance of these factors in establishing the earth's climatic record can be evaluated within the context of the climate system (Hegerl et al. 2007). Climate sensitivity is a commonly used parameter for interpreting climate change predictions. It is characterised as the global surface temperature's equilibrium response to an imposed change in radiative forcing (Meehl et al. 2011). Models with high climate sensitivity, on the other hand, predict a smaller rise in surface temperature under the same CO_2 emission scenario. There is a solution to climate change, but it depends on how big climate feedback will be Stocker et al. (2018). The amount of carbon dioxide in the atmosphere will fluctuate in the future. Another important parameter in determining the rate of temperature rise is the ocean's ability to absorb heat (Raper et al. 2002). As a result, climate change projections are contingent on how energy systems respond to growing greenhouse gas concentrations.

6 Climate Change and the Radiative Forcing

Radiative forcing is a term that refers to an energy imbalance imposed on the earth's climate system externally by human activities (e.g. volcanic emissions, deliberate land modification, change in solar energy output, anthropogenic emission of aerosols, GHG's, and their precursors). It is defined as a radiative reaction to a forcing factor (such as CO_2) that results in temperature fluctuations significantly greater than those observed under normal weather circumstances. Based on various criteria, radiative forcing can be defined by multiple parameters, such as instantaneous, stratospherically adjusted, and effective radiative forcing. It is commonly expressed in terms of watts per square metre (W/m^2) and is not readily visible. It provides a simple quantitative basis for comparing the global average temperature response to different agents. The ability to consume I.R. radiation from the earth through anthropogenic GHGs dictates the increase in radiative forcing, which is usually positive when these gases' concentrations increase. Radiative forcing is dependent on parameters such as the quantity of GHGs in the atmosphere, the wavelengths at which the gas molecules absorb, and the GHGs' absorption per molecule. Radiative forcing is seen as a valuable way to assess climatic effects against radiative disturbances. In order to apply radiative forcing functionally, it is expected that a general link exists between global mean forcing and global average surface temperature (IPCC 1996).

Between pre-industrial (1750) and modern times, the radiative force rises owing to the well-mixed greenhouse gases. Forcing caused by stratospheric ozone (O_3) depletion is estimated to be $-0.15\ Wm^{-2}$ between 1979 and 1997. Although increased levels of CH_4, CO, NOx, and nonmethane hydrocarbons (NMHC) are driving changes in tropospheric O_3, their precise contributions have yet to be determined. To put this in perspective, the global annual mean radiative forcing is estimated to be $0.04\ Wm^{-2}$ for sulphate aerosols, $0.02\ Wm^{-2}$ for biofuels, $0.10\ Wm^{-2}$ for fossil fuel organic carbon aerosols, and $0.20\ Wm^{-2}$ for black carbon aerosols from fossil fuel sources. Mineral dust aerosols are estimated to be between 0.06 and $0.04\ Wm^{-2}$ annually. However, there has been a low scientific understanding of how sulphate aerosols, burning of biomass, and organic carbon fuels affect the radiative forcing.

Global mean radiative forcing estimates have been made for various potential projections (up to 2100) of trace gases and aerosol pollution (Nakićenović et al. 2000). While the figures from different scenarios vary significantly, the findings suggest that the pushing (measured in relation to pre-industrial times in 1750) attributed to trace gases in aggregate is expected to increase. In each scenario, the radiative forcing produced by direct aerosol differs and the direct aerosol effects are estimated to be much less than those of CO_2. The spatial dimensions of potential forcing cannot be predicted. The change in aerosol radiative forcing (both direct and indirect) compared to 2000 is expected to be smaller.

7 Spatio-Temporal Measurement of Climate Change

Since the late 1800s, meteorologists have measured weather characteristics from land-based stations, and, more recently, weather balloons have been used for this purpose. In 1960, meteorologists started gathering weather data by using satellites. Since satellites see a broader and more precise picture above the earth's surface, it is essential for chronicling global climate change. Decades of information have been collected from satellites on pollution, fires, ocean temperature, patterns of sea currents, ice borders, volcanic ash clouds, and many other climatic features. Scientists have built ingenious ways to recreate the past of the earth's environment. Paleo-climatologists use a wide range of methods to learn about the climate of the distant past and even more about the climate of the recent past. Ice cores are the most precious tools that allow scientists to understand the environment on time scales of up to 100,000 years. Similar data for timescales of tens of millions of years are found in ocean sediments. Many other techniques, such as tree rings, are also used to determine local climate information. After scientists collect all the relevant information on the climate, they create climate models that describe the past and forecast the future. Measuring climate change is a complex issue due to a combination of variables such as solar radiation absorption, sea temperature, air mass transfer, clouds, and geographical aspects, such as altitude and ocean closeness, short-term and long-term climate trends. The dynamics of these variables and their relationships are also a fundamental issue and involve evaluating and simulation of theoretical models with high computational costs (Alnaser and Merzaa 2003; McKitrick and Vogelsang 2014; Rincón 2012).

8 Atmospheric Carbon Dioxide (CO_2)

Scientists have been keeping track of atmospheric CO_2 levels since the late 1950s. During this time, its atmospheric concentration has climbed from 280 ppm to over 410 ppm. The evidence implies that this increase is due to the combustion of fossil fuels and human-induced changes to the earth's surface. CO_2 levels in the atmosphere are now foreseen to be the highest in at least 800,000 years and are projected to rise exponentially. Methane and nitrous oxide levels have since increased by about 60% and 25%, respectively, from their pre-industrial levels, becoming the second and third most prominent contributors to anthropogenic forcing of the climate system after CO_2.

9 Global Average Surface Temperature

The average surface temperature of the earth is often used to quantify climate change. Close-surface air temperature measurements from wind stations can be paired with ocean-surface temperature measurements from boats and buoys to record the planet's surface temperature dating back to the mid-nineteenth century. Although the average global surface temperature has been rising in the last century, various estimates by the U.K. Met Office, NASA, NOAA, and Berkeley Earth indicate slightly different methodologies. In terms of data sets, the IPCC concluded that the average of 0.87 °C (0.75–0.99 °C) for the 2006–2015 decade was over the second half of the nineteenth-century average (Laurini 2019). On top of this long-term warming, natural variations can be seen year after year, a reason why scientists typically use at least 30 years to define a true climate change.

10 Rising Sea Levels and Acidifying Oceans

More than 90% of the extra energy absorbed by elevated greenhouse gases in the climate system ends up in the oceans, increasing sea levels. The latest observations show that the rate of global sea-level rise since 1990 has seen a rise, e.g. the sea level in the U.K. is growing at an annual rate of around 1.4 mm. Since the mid-nineteenth century, the oceans have absorbed about 25% of the accumulated CO_2 emissions thus, raising their acidity. Since the pre-industrial era, this has resulted in an acidity rise of approximately 25%, which can impact the capacity of coral species to create shells that have a knock-on effect on entire marine ecosystems.

11 Changing Cryosphere

Satellite measurements of Arctic sea ice level indicate a downward trend, e.g. since 1979, the level of sea ice in the Arctic has dropped by around 13% per decade. The ice in the Arctic has grown smaller and younger, and over the same time, the fraction of Arctic sea ice has dropped by 90% over five years. Greenland and the Antarctic ice sheets have lost mass on the ground and have contributed to the observed increase in the global sea level. Glaciers have decreased, and permafrost areas have warmed to a record high temperature.

12 Weather Events

Significant parts of Europe, Asia, Australia, and the entire world have seen the duration of warm spells increase detectably. Several authors (Karl and Trenberth 2003; King 2004; Kerr 2007; Guttorp 2011; Howe et al. 2013; Hulme et al. 2018; Robinson and Shine 2018) have asserted that the observed patterns of climate change in recent years are primarily anthropogenic (Kaufmann et al. 2011) or maybe as a result of natural trends.

13 Climate Proxies

Paleo-climatologists have developed many groundbreaking methods to collect knowledge on earth's climate history. Scientists use physical and biological clues, called climatic proxies, to unravel past climate trends worldwide or over a particular region. For example, these clues can be found in ice cores, tree rings, sediments and recreate the past environment with astonishing depth and precision. Some climate proxies retain evidence of past temperatures. Using these proxies, paleo-climatologists have reconstructed the past of the earth's environment in various quantities, which cross millions of years. Ice cores contain hundreds of thousands of years of climate data. Ocean floor sediments go back millions of years. Sedimentary rocks from the earth's surface can provide general climate information which goes back to billions of years.

14 Researcher's Opinion on Earth's Climate Destiny

It is a fact that the earth's climate is changing (IPCC 2001a). It is considered the biggest global threat by the scientific community due to its negative consequences on food, water, and shelter (Costello et al. 2009). Since being introduced at the UNGA (1989), climate change has become an issue of paramount significance for analysing the future course of humanity (UNDP 2007/2008). It results from the enhanced CO_2 emissions over the last 50 years, a trend that is expected to continue (EEA 2004; Hulme et al. 2002). Between 1970 and 2004, annual global carbon emissions surged by about 80%, driven by population growth and economic development (IPCC 2007a, b). The 2008 IPCC Assessment Report mentions that the CO_2 concentration in the atmosphere rose to 379 ppm in 2005 from the pre-industrial value of 280 ppm. CO_2 concentration in the atmosphere is directly related to the global temperature increase (Betts et al. 2016) whose average value for the last century has been 0.74 °C, the largest increase in the earth's history till date (Solomon et al. 2007). Doubling atmospheric CO_2 concentrations from pre-industrial levels would result in a catastrophic temperature increase of 1.5–4.5 °C (Voosen 2020). CO_2 emissions are already past midway to the doubling value of 560 ppm, and many models predict reaching the threshold value by 2060. The future course of the earth's climate is being determined by carbon-fueled, ultra-rich industrialists who decide the purpose for which space is utilised on the pretext of economic development (Steffen et al. 2011).

UNFCCC, under the Paris Agreement, affirmed to reduce carbon emissions to a value that would restrict the global temperature rise under 2 °C above pre-industrial levels. However, existing emissions from only six oil companies—ExxonMobil, B.P., Gazprom, Chevron, ConocoPhillips, and Shell—will need more than a quarter of the required air space to meet the 2 °C goal (McKibben 2012), even though they continue to seek new sources of oil and gas. The global average temperature is estimated to rise between 2.7 and 5.2 °C above pre-industrial levels by 2100 under these conditions (Foster et al. 2017; U.N. 2015a, b). An average temperature increase of 1.5 °C may be realised as soon as 2026 (U.N. 2015a, b). Studies indicate that regional warming values may vary depending on local factors (IPCC 2001a). The increase in global mean sea level between 1990 and 2100 is estimated to be 0.09–0.88 m (Learmonth et al. 2006). However, regional variations are higher than the global average sea-level rise (IPCC 2001b). This warming has not occurred uniformly over the planet, particularly mid- and high altitudes have experienced increased average land and sea surface temperatures along with increased precipitation. For example, average air temperatures over the North Sea have risen by 0.8 °C since 1960 (Learmonth et al. 2006), which has resulted in a reduction of ice cover and a rise in sea level.

In contrast, the Southern Ocean and the Eastern Pacific Ocean have maintained cold, deep waters. These areas are also warmer due to rising temperatures, thus eliminating a heat sink (Voosen 2020). Precipitation over mid- and high latitudes increased by 0.5–1% per decade in the twentieth century, while as over tropical areas, the increase is about 0.2–0.3% per decade (IPCC 2001b). In the latter part of the twentieth century, the frequency of severe precipitation events rose by 2–4% in the Northern Hemisphere's mid- and high latitudes (IPCC 2001b). Earth has witnessed far greater climate variations in the past, but the rate at which the current crisis is unfolding has been unprecedented. The impacts of climate change will be most severe in developing countries, where destruction from weather-related disasters can cost up to a quarter of GDP (Guranko 2003; Bulkeley and Newell 2010). The poorer sections in the developing countries are most hit by the impacts of climate change even when they have contributed least to the problem. Sea level has been rising, evidently noticeable in the low-lying areas and small island states that face the threat of inundation (Uan 2013) like Maldives and Tuvalu, which could be lost to the whole nations sea-level rise (Rajamani 2010), rendering their inhabitants homeless. Other areas facing the loss of landmass to sea-level rise are coasts of the Americas, the Gulf of Maxico, the Atlantic, the Baltic, the Mediterranean, Asian Mega Delta, small island regions, and other low-lying urban areas (FAO 2009a, b). Climate change is also predicted to impede agriculture by variations in the temperature and rainfall patterns, with the tropical regions experiencing negative effects while temperate regions having longer growing seasons and increased agricultural production (Darwin 2001; Devereux and Edwards 2004; FAO 1996). By the 2080s, the associated food shortages would expose an additional 5–170 million people to starvation (Parry et al. 1999, 2004; Rosenzweig and Parry 1994). Global temperature increases and precipitation patterns would increase the magnitude and severity of vector-borne pests (Thornton et al. 2009). Water scarcity resulting from climate change would force 64% of the world's population to live under water stress conditions by 2025 (Rosegrant et al. 2002). Climate change is expected to drive most terrestrial and marine species towards polar regions, thereby expanding the range of organisms living in warm areas and contracting those of colder regions (FAO 2009a, b). Additional projected effects of climate change on oceans and seas include changes in ocean circulation, loss of sea ice cover, changed salinity, CO_2 concentrations, pH, storm frequency, and severity of climate patterns (FRS 1998; Hulme et al. 2002; ICES 2004; IPCC 2001a). Predicting the future implications of climate change provides an insight into how human actions interfere with natural set-ups, the scale of responses of the earth towards such activities, the potential of humankind to get affected by climate-related events, and possible options of adaptation and mitigation measures that can be employed.

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Threats to Humanity from Climate Change

M. M. Majedul Islam

Abstract It is quite evident that our climate is changing rapidly. Climate change is not merely an environmental issue, but is likely to result in world-wide depletion of various natural systems, e.g. soil fertility, aquifers, inland fisheries, and biodiversity. It affects our economic activities, infrastructure and managed ecosystems, natural environments and poses risks to human health and well-being. The health impacts include heat stress from heatwaves; injuries from extreme weather events (e.g. storms, floods, fires); outbreaks of infectious diseases due to changing water-borne and vector-borne diseases; malnutrition due to decline in food production and availability. Since the climate continues to change, the risks and threats to humanity continue to increase. Practical measures to reduce greenhouse gas emissions and mitigate risks from climate change are urgently needed.

Keywords Threats · Risks · Climate change · Food production · Diseases · Heatwaves

1 Introduction

There is rising evidence that the climate is changing rapidly. Climate change is not merely seen as an environmental or economic issue, but over the last couple of decades, its threat has become larger and more robust. The increasing emission of greenhouse gases (GHGs), such as carbon dioxide, nitrous oxide, methane and halocarbons, is causing changes in many climate hazards that affect humanity in several ways. Mora et al. (2018) found traceable evidence for 467 hazards or pathways by which climate hazards have impacted ecosystems, food security, economy, infrastructure, biodiversity and human health. Such hazards include a global rise in average temperature, and increased frequency and intensity of precipitation, floods, cyclones, hurricanes, storm surges, sea-level rise, heat waves, droughts, and an altered

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distribution of food-borne and vector-borne infectious diseases. Anthropogenic influences alter Earth's ecosystem and biophysical system, which is evident from ground-level ozone depletion, depletion of freshwater supplies, biodiversity losses, stresses on food-producing systems, and organic distribution pollutants and microbiological hazards (WHO 2003). By 2100, the world's human population will be exposed concurrently to one of these hazards with the most considerable magnitude. It was also highlighted that GHG emissions impart a significant threat to humanity by intensifying multiple hazards with some tropical coastal areas facing many simultaneous hazards that can result in compounding thr threats.

Rising temperatures and sea levels, change in precipitation pattern, increasing frequency and intensity of extreme weather events, and melting ice disrupt people's lives and damages the economy. Climate change is considered as a real threat to humanity. Changes in climatic factors and weather extremes affect our environment and health, economy and well-being in different ways (Table 1). Climate

Table 1 Impact of climate change and extreme events on humanity

Climatic factors	Exposure pathways	Impact on humanity
Increasing temperatures Extreme heat events	Extreme heat, worsened air quality	Increase in heat-related illness and death Elevated risk of cardiovascular and respiratory illnesses and death
Rising sea-level Frequent and intense extreme precipitation, cyclones, hurricanes and storm surges and associated flooding	Contaminated water; salinity intrusion; disruption of houses and other infrastructures	Increased waterborne diseases; Reduced agricultural production; Injuries; Drowning; Preterm birth and low birth weight Infrastructure disruptions and post-event disease spread; Negative impact of mental health and well-being
Change in temperature extremes and seasonal weather pattern	Change in infectious agents	Increased vector-borne diseases
Change in precipitation pattern and run-off	Recreational water and shellfish contaminated with waterborne pathogens	Increased water and foodborne diseases
Draughts	Reduced water quantity Reduced air quality	Reduced agricultural production; Respiratory impacts related to reduced air quality; Mental health impacts
Wildfires	Rising temperatures and hotter, drier summers increase the frequency and intensity of wildfires	Smoke inhalation; Burns and other traumatic injuries Asthma exacerbations Mental health impacts

change affects people in different ways and different degrees. It increases the pre-existing vulnerabilities of elderly, women, fishermen, marginal farmers and people living in informal settlements (Chersich et al. 2018). Susceptibility to the risks and threats associated with climate change can also exacerbate existing socio-economic challenges. It affects the food price by making precipitation patterns unpredictable and causing more intense cyclones, hurricanes and storm surges which damages crops. Climate change-induced extreme weather events are responsible for the displacement of thousands of people every year.

The impact of climate change on human health includes death and illness from extreme heat and cold, mortality from natural disasters, food-borne and waterborne infectious diseases, and low labor productivity (Hasegawa et al. 2016). Climate change harms agricultural production, which in turn increases the risk of hunger and malnutrition. Also, malnutrition due to climate change has negative health consequences in underweight children, and the worst case may lead to child mortality (Hasegawa et al. 2016).

Climatologists forecast a further increase in global warming and the associated changes in precipitation pattern and climatic variability during the current century and beyond that will result in an increased climatic impact on human health. Since the effects and threats of climate change on human health are projected to worsen over time, some existing threats will intensify, and new hazards may emerge. Improving our understanding of how climate change may affect human health and well-being can inform decisions about mitigation and adaptation of future climate change, help design research plans, and set priorities for public health protection.

2 Our Changing Climate

It is unequivocal that the Earth is warming. Numerous observations of air and water temperatures, sea level, and ice melting have shown unprecedented changes over the past several decades (USGCRP 2016). The concept of climate change includes increases and decreases in temperature, precipitation pattern, extreme weather events (e.g. cyclones, hurricanes, storm surges, heatwaves, draughts), and other climatic factors.

Future climate change projections are based on results from global climate models. These models are applied to project how climate is expected to change under different plausible scenarios. Scenarios are sets of plausible futures regarding how the future is likely to unfold from present conditions under different human choices (Polasky et al. 2011). These scenarios consider different trajectories for demographic, socio-economic and technological changes; and describe future changes in greenhouse gas emissions, land use, and climatic factors (e.g. temperature, precipitation). Several General Circulation Models (GCMs) describe present and future changes in climate on a global scale (Islam et al. 2018a). With the help of GCMs, changes in temperature, precipitation and sea-level rise can be simulated; and the output from the GCMs are used in climate change impact assessments.

The fifth assessment report of the Intergovernmental Panel on Climate Change used four Representative Concentration Pathways (RCPs) for climate change projections, which describe four possible trajectories in greenhouse gas emissions. The RCPs describe trajectories in greenhouse gas emissions (consistent with radiative forcing) and the subsequent changes in climatic factors (e.g. temperature and precipitation) (Van Vuuren et al. 2011; Islam et al. 2018b). Actual future emissions, and the resulting extent of future climate change, will primarily be dependent on choices people make about emissions.

3 Extreme Event Impacts

Extreme events are weather and climate-related events that rarely occur at a given location and have large impacts on human health and socio-economy (Bell et al. 2018). Some of these events include heat waves, droughts, wildfires, flooding, storm surges, cyclones and hurricanes. Extreme events affect humanity by causing injury, illness, and death (e.g. drowning during floods) and economic damages (Table 1). Extreme events can also disrupt essential infrastructure access and functionality, such as public health facilities, transportation, energy grids, and wastewater treatment systems. Disruption of infrastructure can hamper evacuation from extreme event affected areas and impede food and life-saving medicine delivery.

Climate change influences the functioning of most ecosystems on earth, and the species living there. Although most of the health impacts of climate change are adverse, some of these impacts are beneficial. For example, milder winters would likely reduce the seasonal winter-time cold related mortalities in the temperate region. In contrast, in the tropical areas, a further increase in temperatures might decrease mosquito populations' viability that transmits diseases (WHO 2003). Franchini and Mannucci (2015) found that increasing temperature in the temperate region may reduce cold-related diseases (such as pneumonia, bronchitis and arthritis). Still, these benefits are not adequate to compensate for the risks associated with global warming.

Many human diseases, such as cardiovascular and respiratory illnesses due to heatwaves, the altered transmission of infectious diseases, and malnutrition from crop failures, are associated with climate change. Climate change is also the cause of behavioural and mental health problems, such as anxiety, depression, post-traumatic stress and suicide. For example, after Hurricane Katrina in the USA in 2005, older people with pre-existing mental illness had a seven times higher risk of worsening their mental illness (Introcaso 2018).

The frequency, intensity and duration of extreme weather events, such as rising temperatures, heavy rainfall and droughts are changing with climate change, which will continue to change in future (Bell et al. 2018). This indicates that areas already experiencing such health-threatening extreme weather or climate events are likely to exacerbate health problems by increasing temperatures and increasing storm frequency and intensity. It also means that certain areas will experience a new climate and weather-related health threats. For example, areas previously inexperienced in waterborne diseases because of cooler water temperatures may experience such disease in the future as rising water temperatures provide a favourable condition for the microorganisms responsible for causing those diseases. Therefore, climate change can affect human health mainly in two ways: by worsening the frequency or severity of existing health complications, and by creating unprecedented health threats in places that have not previously been (USGCRP 2016) in such risks.

Health impacts may also happen before or after such an event, as a person can be involved in disaster preparedness and post-event cleanup activities that can put their health at risk. Health risks may also appear long after an extreme event due to property and infrastructure damage, destruction of assets, environmental degradation, etc. Extreme events also cause health risks when multiple events co-occur or occur in quick succession in any area.

The pathways of extreme event impacts on human health, business and economic losses are diverse and complex (Bell et al. 2018). Extreme events related to health effects and severity vary with geographic location, environmental factors, socio-economic condition and demographics of a given community. Changes in population size, ethnic composition, and age affect people's health status. Educational qualification, poverty, healthcare access, and other discriminations contribute to the incidence and prevalence of health conditions. For example, the life expectancy of minority populations having higher rates of hypertension, smoking habit, and diabetes may decrease by the effects of climate change-induced increased temperature and air pollution (USGCRP 2016). In areas where the community's health or socio-economic status is getting worse, climate change may exacerbate their health problems. On the contrary, in places where people's health conditions or socio-economic status is improving, climate change may affect by slowing or reducing that improvement (Luber et al. 2014).

Population growth, urbanization and migration can put more people vulnerable to the health risk of climate change, particularly as more people are located in and around vulnerable areas like coastal, low-lying, or flood-prone areas; wildfire-prone zones; drought-stricken regions; and densely populated urban areas. The people living near the poverty line may have an increased risk of health impacts from climate change. Poor economic conditions can make it very difficult to respond to extreme weather events, particularly when rebuilding homes and businesses is required (USGCRP 2016).

To understand how climate change exacerbates health problems, climate change health impacts assessment is required. In-depth study and research regarding the impacts of extreme events and climate change on socio-economy, human health, and well-being are needed for effective planning, mitigation, and adaptation to climate change. Mathematical model-based scenario analysis that includes projected changes in people's health and socio-economic status can provide useful insights into the impact of non-climate factors on human health (Islam et al., 2018b). Since pre-existing health conditions, age, socio-economic status etc. influence vulnerability to weather and climate-related health impacts (Chersich et al. 2018), climate change health risk assessments must be performed considering projected changes in these factors. Public health risk can be quantified using hazard identification, exposure assessment and dose–response relationship (Islam and Islam 2020). The future health risk from climate change can be quantified by using three values: (1) the baseline data of the health impact, (2) the projected change in exposure, and (3) the exposure–response function, which is a projection of how a health risk changes with future modifications in exposures (USGCRP 2016).

3.1 Temperature Related Threats

Global temperatures have been continuously increasing and reaching a new level almost every year since the last couple of decades (Orimoloye et al. 2019). This is likely to cause increased mortality from heat and a potential decrease in mortality from cold, particularly for children, the elderly, immuno-compromised, disabled, minorities and the poor due to their vulnerablity to these changes (USGCRP 2016). Days that are hotter than the average summer temperature or colder than the average winter temperature leads to increased morbidity and mortality by hindering the body's temperature regulation ability or by inducing other health complications (USGCRP 2016).

Higher temperatures cause heat exhaustion, heat cramps, heat stroke, hyperthermia, and dehydration, leading to death in extreme cases. Higher temperature and radiation cause different heat-related diseases (e.g. heat stroke, heart disease, skin cancer, diarrhoea) which might be influenced strongly by extreme weather events (Orimoloye et al. 2019). Temperature extremes can also worsen pre-existing conditions such as cardiovascular, respiratory, kidney and diabetes-related conditions (USGCRP 2016; Introcaso 2018).

Higher temperatures also affect mosquitoes, ticks, fleas and rodents that transmit vector-borne diseases. For example, warmer temperatures shorten the reproductive cycle of mosquitoes. Global warming also influences the fate, transmission, viability and multiplication of waterborne pathogens (Introcaso 2018).

Warmer average temperatures can alter the spatial and seasonal distribution of vector-borne (e.g. malaria and dengue fever), and food-borne infections diseases (e.g. salmonellosis) which peak in summer. Human cardiopulmonary system and gastrointestinal tract are particularly vulnerable to warmer temperature's adverse effects (Franchini and Mannucci 2015).

There is little information on how heat-related illnesses will change with projected increases in temperature. However, hospital records show that patients suffering from respiratory, urinary, renal and genital complications are increasing. Kidney stone problem has been associated with high temperatures, possibly because of dehydration resulting in a higher concentration of salts that form the kidney stones (Li et al. 2012). The decrease in illness and deaths from a decrease in winter cold has not been studied well, but the decrease in deaths from cold is likely to be smaller than the increase in deaths due to increased heat (Li et al. 2012; Luber et al. 2014).

An increasing number of studies has generally projected a net increase in deaths from a warming climate. Studies show that an additional extreme hot day may lead to more deaths than an additional extreme cold day, and the decrease in extreme cold deaths is limited as the total number of cold deaths is already very less.

Impacts of extreme temperature vary with geographical locations and populations of concern. Certain populations are more at risk of exposure to temperature extremes due to their sensitivity to temperature gradients and limitations to their adaption capacity to change in climate conditions. A developed country's population is usually less sensitive to heat extreme due to increased access to air conditioning and public healthcare facilities. This trend of increasing adaptive capacity and tolerance is projected to continue, and the future increase in mortality rate is therefore expected to reduce. However, adaptation is not unlimited and most recent studies have projected a rise in mortality, even assumptions regarding future adaptation have been taken into account (Mills et al. 2015). Older people are at higher risk of extreme temperature-related morbidity and mortality, particularly those who have pre-existing health complications, take medications (that reduce thermoregulation or cause nerve blockage) or those with limited physical movement. An increased risk of mortality from respiratory and cardiovascular diseases has been observed in older people (over 65 years old) during extreme temperatures because of inefficient thermoregulation (Åström et al. 2011; USGCRP 2016). Association between high temperatures and cardiovascular and respiratory hospitalizations in older people has also been identified (Åström et al. 2011).

The health complications observed in children exposed to extreme temperature include dehydration, electrolyte imbalance, heat stress, fever, and renal disease. Both hot and cold temperatures affect infectious and respiratory diseases in children. Reduced thermoregulation and cardiovascular output, and increased metabolism are physiological factors that cause children's vulnerability to extreme heat. Pregnant women are also vulnerable to extreme heat as elevated exposure to heat can cause dehydration, leading to release of labour-inducing hormones (Beltran et al. 2014). Temperature extremes may also result in premature birth, low birth weight and infant mortality (USGCRP 2016).

Outdoor workers are at increased risk of illness and deaths from temperature extremes, mainly when they involve vigorous activities. Extreme heatwaves can exacerbate mental, cognitive and behavioural disorders. Some medications interfere with thermoregulation, therefore increase vulnerability to excessive heat. One study (Martin-Latry et al. 2007) in Australia reported that hospital admissions with behavioural and mental disorders increased by over 7% due to heat above 80 °F.

3.2 Heavy Rainfall and Flood

Floods impact individuals and communities and have adverse socio-economic and environmental consequences (Table 2). The effects of floods are related to location, topography, duration, extent of flooding, human demographics and characteristics of

Table 2 Types of losses due to floods

	Direct loss	Indirect loss
Monetary loss	Destruction of buildings, infrastructure, assets, livestock, crops etc.	Disruption to transport, environmental degradation, loss of value added in business etc.
Non-monetary loss	Loss of lives, injuries, infection, water-related illnesses, damage to cultural or heritage sites, ecological damage etc.	Stress and anxiety, mental health and well-being, disruption to living, loss of cultural and environmental sites, loss of community, etc.

the affected natural and built environment (Du et al. 2010). Flooding associated with heavy rainfall events has various impacts on the humans, including injury, drowning and death. Floodwater is often mixed with sewage, which can impure drinking water with chemicals, heavy metal and pathogenic microorganisms leading to infection, illness and death (Islam and Islam 2020). The flood can damage the bridges, railways and road transport networks. Damage to infrastructure can cause long-term impacts, e.g. disruptions to the power supply, transport, communication, clean water supply, wastewater treatment facilities and, health care and education.

Further, it can cause widespread damage to crops and livestock due to water-logging and delayed harvesting. It is further intensified by disruption to transport because of inundated road and damaged bridge/culverts. Flood damage to roads and rail networks can have significant impacts on national economies.

The flood may have some positive impact. Flooding can increase agricultural production by recharging groundwater aquifer, by filling wetlands and improving soil fertility through silt deposition. Floods maintain ecosystem functions and biodiversity. Flood carries sediment and nutrients from lands and discharges into the aquatic environment (Islam et al. 2018a). Floods support increased fish production through breeding, migration and dispersal. The environmental benefits of flooding also include supporting ecosystem services and maintenance of recreational environments.

3.3 Severe Storms

Warmer air holds more water, and rising temperatures increase surface evaporation, increasing the frequency and intensity of rainfall events, resulting in cyclones, hurricanes, typhoons and storm surges. Cyclones, hurricanes and storm surges are a major threat for coastal communities worldwide. About two million people have died in the last century, and millions have been injured worldwide from severe tropical storms, such as cyclones, hurricanes, and typhoons (Haque et al. 2012). Hurricane Maria in 2017 accounted for nearly 3000 deaths across Puerto Rico. In recent years hurricane Harvey, Irma and Maria collectively caused over $300 billion damage (Introcaso 2018). Globally, the frequency and intensity of severe storms may be increasing because of higher sea surface temperatures associated with global warming. According to recent research (Patricola and Wehner 2018), global warming will cause hurricanes to become even more deadly by intensifying precipitation by as high as 10% and wind speeds by 25 mph.

3.4 Sea Level Rise

The current rising rate in the Global Mean Sea Level is more significant than at any time in history. If the Greenland ice sheet completely melts, global sea level would rise by at least seven meters and just half a metre rise in sea level would risk the survival of the whole human population of many small Island nations. Presently about 145 million people worldwide live one meter or less above sea level, and about 40% of the world's population lives within 100 kms of the coast. As the global coastal population is projected to surpass one billion in this century, sea-level rise would be among the most severe and lasting consequences of climate change (Hauer et al. 2020). Sea level rise affects coastal people through flooding, when river water cannot flow into the sea/ocean and when seawater surges onto the surrounding land during storm surges (Siegert 2017). If the seawater enters farms and reservoirs, it contaminates the drinking water supply and destroys crops. High population concentration in the coastal zone increases people's vulnerability to sea-level rise and other coastal hazards such as storm surges. Sea level rise may even influence the migration of millions of people (Hauer et al. 2020). Rising seas or flooding may destroy stormwater disposal and wastewater treatment, resulting in epidemics of waterborne diseases caused by pathogenic bacteria, viruses and protozoa.

3.5 Droughts and Fires

Heat and droughts increase the prevalence, intensity and duration of wildfires worldwide. In recent years many areas of the world have experienced deadliest droughts. For example, since 2000, a higher frequency of drought incidence has been observed in the Amazon than the last century, and these are expected to intensify (Machado-Silva et al. 2020). The recent wildfires in Australia, Amazon and California were the deadliest by far in history (Introcaso 2018). The amount of carbon these fires emitted could be massive, which might further exacerbate climate change trends. Such fires exposed local communities to hazardous air quality that might lead to serious health consequences, including respiratory illnesses. Heat, drought and wildfires contribute to worsening of air quality that may result in acute respiratory illnesses (e.g. asthma, acute bronchitis and pneumonia) and cause hundreds of thousands of premature deaths worldwide. The study revealed that in 2013, air pollution caused an estimated one-third of deaths in the 74 leading Chinese cities (Fang et al. 2016).

4 Air Quality Impacts

Air quality is strongly associated with weather, and therefore sensitive to climate change. Changing climate can degrade air quality by concentrating pollutants in the stratosphere (Hassan et al. 2016). Polluted air can adversely affect human respiratory and cardiovascular systems. Health effects of climate change vary with population group, location and human capability of responses to health problems. In recent years, the incidence of respiratory illnesses has grown remarkably all over the world. Climate change-induced air pollution may aggravate respiratory complications. Most of the allergic respiratory diseases such as asthma and rhinitis are seasonal with climatic factors. Climate change may exacerbate such allergic reactions. Human being including children, the elderly, and people with pre-existing asthma and cardiovascular problems are vulnerable to air pollution. Air pollution can reduce lung functions, aggravation of respiratory symptoms, and increase hospital admission for cardiovascular and respiratory illnesses and even death (Kheirbek et al. 2013).

Climate change affects human health by increasing air pollutants such as ground-level ozone (a component of smog) and particulate matter in different Earth regions. Ground-level ozone is associated with many health problems, including diminished lung function, increased hospital admissions for asthma, and increases in premature deaths (USGCRP 2016). Climate change-induced large and severe wildfires can also reduce air quality substantially and affect human health in different ways. Smoke exposure increases acute respiratory and cardiovascular illnesse. The frequency of wildfires is likely to grow with a more prevalent and severe drought. Exposure to allergens causes health problems for many people. When a sensitive individual is exposed to allergens and air pollutants simultaneously, allergic reactions become more prevalent and severe. Increased air pollution often deteriorates the effects of increased allergens associated with climate change.

Future climate change may exacerbate health impacts by increasing the frequency, intensity, and duration of extreme weather events with increased air pollution exposure. With global warming, both the frequency and intensity of heatwaves are expected to increase. During episodes of heat waves, air pollution will subsequently increase and will exacerbate health problems.

Storms can also deteriorate air quality by increasing particulate matter levels in urban areas. The aerosol particles can cause storm clouds to linger and increase temperature at night due to the convection process. Kwon et al. (2002) reported that dust storm events in South Korea were associated with a risk of death from cardiovascular and respiratory problems.

5 Water Quality Impacts

Climate change is expected to affect water resources in different ways, increasing people's vulnerability to waterborne diseases caused by bacteria, viruses, and protozoans (Table 3). Toxins produced by certain harmful algae and cyanobacteria and chemicals introduced into the aquatic environment by human activities can cause water-related diseases. Exposure pathways include ingestion, direct contact with contaminated drinking/recreational water, and contaminated fish/shellfish consumption. The primary sources of water contamination are human and animal waste and agricultural activities, including manures and fertilizers (Islam et al. 2019). Runoff and flooding resulting from climate change-induced extreme precipitation, cyclones, hurricanes and storm surges are likely to increase water contamination risks. Contamination occurs when agents of water-related illness and nutrients (e.g. nitrogen, and phosphorus) are carried from urban and agricultural areas into water sources (Fig. 1).

Table 3 Climatic factors and waterborne pathogens that cause water-related diseases

Waterborne pathogens/agents	Exposure pathway	Climatic factors	Health outcomes
Toxic algae (e.g. Cyanobacteria, diatoms)	Drinking water, Recreational waters, Fish and shellfish	Increased water temperature, ocean surface currents, ocean acidification	Asthma, eye irritations, Gastrointestinal and neurologic illness caused by shellfish poisoning
Enteric bacteria (e.g. Salmonella, Campylobacter species, Toxigenic Escherichia coli, Cryptosporidium, staphylococci)	Drinking water, Recreational waters, Shellfish	Temperature (both increase and decrease), heavy rainfall, flooding	Gastroenteritis, Skin infections
Vibrio species (e.g. v. cholera, V. parahaemolyticus)	Recreational waters, Shellfish	Increased water temperature, sea-level rise, precipitation patterns and coastal salinity fluctuation	Gastroenteritis, Septicemia, Skin, eye, and ear infections
Protozon parasites (Giardia, Entamoeba histolytica)	Recreational waters, Shellfish	Temperature (both increase and decrease), heavy rainfall, flooding	Gastroenteritis
Enteric viruses (e.g. enteroviruses, rotaviruses, adenovirus, noroviruses)	Drinking water, Recreational waters Shellfish	Heavy precipitation, flooding, increased water temperature	Gastrointestinal illness, paralysis; infection of heart or other organs

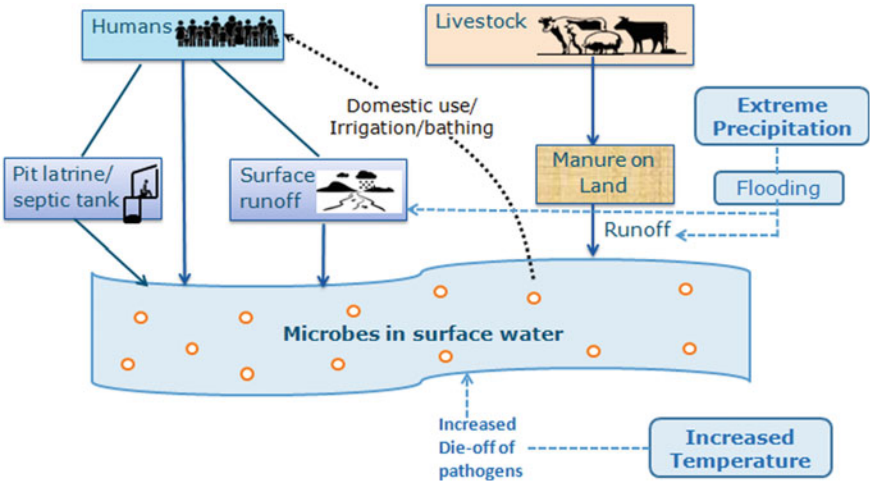

Fig. 1 Sources, pathways and impact of climate change on microorganisms in surface water

Climatic factors or drivers include temperature, precipitation and related runoff, cyclones, hurricanes, and storm surge that affect the survival, growth, proliferation, spread and virulence of pathogens/agents of water-related diseases. Exposure to contaminated water, fish, or shellfish causing diseases depends on various factors, including human behaviour, socio-economic and physiological condition that may influence a person's sensitivity, and adaptive capacity (USGCRP 2016). Primary health outcomes results by waterborne pathogens/agents include gastrointestinal diseases and skin infections. Water quality monitoring and management, wastewater treatment, beach closures etc. can reduce the risk of exposure and illness from contaminated water (Islam et al. 2018c).

6 Vector-Borne Illnesses

Vector-borne illnesses are transmitted by vectors, such as mosquitoes, fleas and ticks. These vectors usually carry infectious microorganisms such as viruses, bacteria, and protozoa, transmitted from one host to another. The prevalence, temporality and distribution of vector-borne illnesses are influenced substantially by climatic factors, particularly increased or decreased temperature and change in precipitation patterns. Climate change has both short and long term impacts on transmission of vector-borne disease. The variability in climatic factors alter transmission and seasonality of vector-borne diseases and interact with some other factors, such as how pathogenic microorganisms adapt and change, ecosystem and land use changes, and availability of hosts demographics, human behaviour, and their adaptive capacity.

All these make it difficult to predict climate change's actual impact on the prevalence and distribution of vector-borne diseases.

7 Impact on Food Safety and Nutrition

Supply of safe and nutritious food is a fundamental element of food security. Climate change is likely to affect global food security by reducing food production, disrupting food supply channel and decreasing access to food, which increases the risk of hunger and malnutrition. Malnutrition due to climate change can lead to underweight children and in the worst case may lead to child mortality, particularly in low-income countries (Hasegawa et al. 2016).

The impacts of climate change on food safety, nutrition, and distribution is less emphasized and less reported (Brown et al. 2015). Increasing CO_2 and climate change can alter our food safety, nutrition, and distribution through two main pathways. The first one is associated with global warming and the associated changes in climate and weather patterns (USGCRP 2016). Current and projected changes in climate, weather patterns, and physical environment have adverse consequences on people's environmental quality, food safety, nutrition, and livelihood. The other pathway is through CO_2 fertilization impact on plant photosynthesis. A higher level of CO_2 can stimulate carbohydrate production and growth in some plants but can lower the amount of protein and essential minerals in many other cereal crops, such as wheat, rice, and potatoes, which has negative consequences on human nutrition (USGCRP 2016).

8 Impact on Mental Health and Well-Being

The impact of climate change on mental health and people's well-being are substantial. Mental health effects of climate change can range from minimal stress to clinical disorders including anxiety, depression, post-traumatic stress and suicidality. The mental health and well-being related impacts of climate change often coincide and interact with other societal and environmental stressors that make it difficult to understand the overall effects of climate change on people's health, mental health and well-being. Recent research (Hrabok et al. 2020) confirmed that certain risk factors, such as gender, education, socio-economic status, pre-existing mental health symptoms were associated with greater vulnerability to mental health following deadly natural disasters.

9 Conclusion

The Paris climate agreement aims to hold global warming well below 2 °C and to pursue efforts to limit it to 1.5 °C. The recent Intergovernmental Panel on Climate Change (IPCC) report concluded that if the current rate of GHG emission continues, temperatures will rise to 1.5 °C above pre-industrial levels by 2040. To avoid this, the IPCC reported that GHG pollution must be reduced by 45% from 2010 levels by 2030, and by 100% by 2050. If we fail to implement appropriate mitigation actions, the temperature will likely increase as high as 4 °C by the end of this century. At 4 °C, for example, 44% of vertebrates lose half of their geographic range, plants and insects over two-thirds, global crops production falls dramatically and the global economy contracts by over 30%. Climate change threatens to slow, halt or even reverses the progress and socio-economic development of a country.

Recent scientific evidence shows that our planet is already being impacted by climate change in the form of extreme weather events, food shortages from crop failures, or altered distribution of infectious diseases. The impact will continue on future generations, and each day we delay addressing the situation means more destruction to our planet and damage to humanity. Therefore, it is essential to take practical measures to reduce greenhouse gas emissions and mitigate climate change risks. Reducing greenhouse gas emissions can help protect human health and well-being by reducing impacts on our environment. Improved understanding of the association between climate change and extreme weather-related illness can help reduce vulnerability. It is also essential to set and update priorities, mobilize resources and build capacity for research and development on climate change adaptation and mitigation.

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Understanding the Causes of Climatic Change in the Environment

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Abstract Climate change, caused by natural (climate variability, volcanic eruptions, change in earth orbits and ocean circulation), and anthropogenic activities (industrial and energy production emissions, greenhouse gasses from vehicles and agriculture) is a hot topic for scientific discussions nowadays due to its broader effects and consequences. It causes adverse impacts on ecosystems ranging from sea level rise to agro-ecological zone shifting. It adversely affects the agricultural productivity, microbial diversity, soil organic matter, droughts, shifting of agro-ecological zones, and loss in crop yield to even severe disasters like food security problems. Other effects on the environment include extreme weather events like floods, abrupt and intensive rains and storms, forest fires, loss of biodiversity and habitats. In this chapter, authors have tried to discuss climate change with all its contributing factors.

Keywords Fossil fuels · Global warming · Greenhouse gasses · Natural phenomena

1 Introduction

From the North to the south pole, planet earth is warming. Since 1906, the global average surface temperature has increased by 0.9 °C to and even more in comparatively sensitive polar regions. The impacts of rising temperatures appear in the form of melting glaciers and sea ice, sea level rise, shifting precipitation patterns, and biodiversity loss and shifting of agricultural zones. Global warming and climate change are considered synonyms, but scientists prefer to use the term climate change, when addressing the issue. Climate change induces rise in temperature, resulting in extreme weather events and, shifting in wildlife population and their habitats. These changes emerge due to human interruptions in the atmosphere by supplying excessive GHGs and causing heat-trapping phenomenas (Change 2017).

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Scientifically, climate change is considered as the alteration in the climatic arrangements over long periods. These alterations could be because of the natural processes, like variability in suns radiations, volcanic eruptions, modifications in the climate system or because of the activities by humans pollution, industrialization and land use changes (Hughes et al. 2018). On earth, sun's energy is the most significant driver of the climatic system. This energy depends on its amount released by the sun and the area between the sun and earth as, some part of this sunlight is absorbed by the earths surface, and some are reflected back. Aerosols, the suspended particles, increase this phenomenon of reflection resulting in greenhouse effect (Mi et al. 2019). It happens due to GHGs, like water vapours, carbon dioxide (CO_2) and methane (CH_4) and is essential for the sustenance of life on earth by maiking it livable (Farooqi et al. 2018; Freeman et al. 2018). CO_2 is the most significant GHG, as it is three times that of the pre-industrial levels. Methane, another GHG has more warming potential than all other GHGs and remains in the atmosphere for around a decade but is found in minute quantities in the atmosphere. However, CO_2 can persist for almost 100 years or more, so even if we stop its emissions, the earth will continue to warm up from these gases (Seager et al. 2019; Farooqi et al. 2020).

Raising awareness about climate change is often known as the main rule for climate change mitigation and adaptation. There is a always small risk of climate change on individuals because of the increased awareness about the causes of climate change (Luís et al. 2018).

2 Climate Change: Origin and Concepts

Climate change is a multidimensional subject with paradoxical dimensions. Although there is a very positive consensus on the actual happening of climate change still many societies do not accept climate change to be real. In industrialized countries, most people believe that climate change is not a real phenomenon and mere a goodbye-product of the Industrial Revolution. In non-industrialized and less educated nations, it is thought that climate is cannot be altered by human interventions but is solely controlled by divine forces. In this divergent society, scientist and journalists who, study and report on climate change have intricate work to do. They simultaneously have to work on the study and dissemination to society that does not accept their findings.

Intergovernmental Panel on Climate Change (IPCC) is the primary source of scientific information on climate change. It came into existence in 1988 by the United Nations Environment Program (UNEP) and World Meteorological Organization (WMO). IPCC itself does not do research; it only gathers the available information and invites different experts to review the information in the context of climate change. IPCC was the first body which concluded in 2007 that climate change is a real phenomenon, and its future impacts could be abrupt, lethal and irreversible. According to the IPCC, numerous climate change impacts vary in their magnitude (Marselle et al. 2019).

3 Causes of Climate Change

Some gases called GHG's present in the atmosphere act like a blanket and trap suns radiations and stop them from radiating back into space. Many of these GHGs occur naturally and are necessary to maintain temperature, favourable for sustainability of life. But, human activity has increased their concentrations above the optimum levels in the atmosphere, especially that of CO_2, CH_4, nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) (Fig. 1). Top scientists worldwide have proposed that human activities are the primary sources of GHGs and the leading cause of CC till the middle of the century (industrial revolution age). And a rise of 2 °C in temperature has occured after the industrial period compared to the pre-industrial times and due to this temperature increase, the international community has recognized the need to keep warming below 2 °C.

3.1 Natural

3.1.1 Volcanic Eruptions

The possibilities of more severe events of volcanism and ash clouds pose issues for the local and regional climate and aviation industry. The main mechanisms involved in eventual and prolonged volcanism events with environmental relations should be explored as these mechanisms demonstrate a dynamic and integrated framework of volcanisms. These volcanoes can, directly and indirectly, affect the environment and

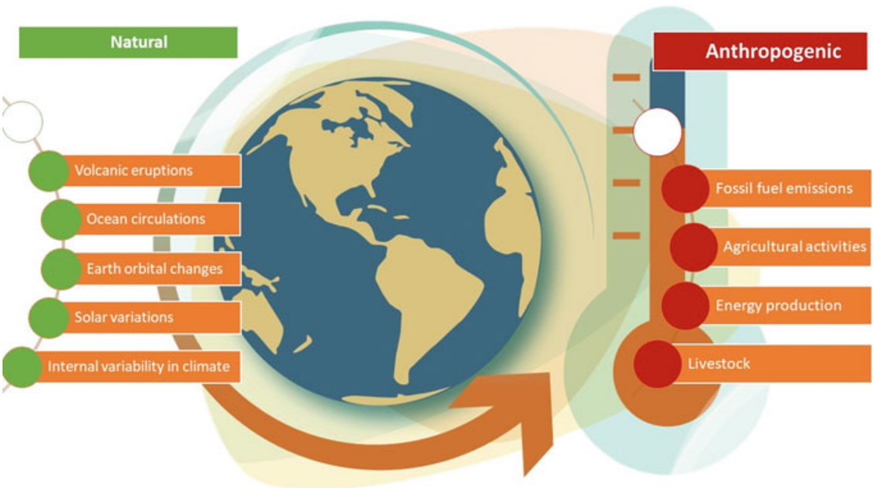

Fig. 1 Cause of climate change

cause CC. Long-term or prolonged volcanism events can cause CC on a regional and global scale by increasing the excessive concentrations of stratospheric aerosols and fine ash particles, as reported in 1991 Pinatubo eruption. The consequences on the atmosphere due to prolonged and explosive volcanic eruptions are more critical due to their prolonged effects and supply of pollutants to the atmosphere and their cross-boundary movements. The rise in volcanism and cross-boundary movement of pollutants could contribute to more frequent CC related extreme weather events across Europe (Cooper et al. 2018) (Table 1).

Eruptions of Tambora (Indonesia) in 1815 had significant impacts on the global environment, causing Europe and North America's 1816 as a year without cropping season. It was a horrific event due to which thousands of citizens lost their lives. Climate models respond to recommended Tambora-like forcing by reinforcing the winter stratospheric polar vortex, accelerating global cooling and water cycle, worsening summer monsoon circulation, improving the Atlantic South Overturning Circulation and decreasing atmospheric CO_2. More excellent knowledge of climate processes arose, integrating observations, climate proxies and model simulations for Tambora's scenario (Raible et al. 2016).

Extratropical volcanic eruptions are typically considered less significant in terms of effects than coastal eruptions in terms of atmospheric/surface cooling at larger scales. It has been proved that explosive extratropical eruptions have caused more significant hemispheric cooling than tropical eruptions in comparison to their estimated stratospheric injection using ice-core and tree rings in the Northern Hemisphere. Stratospheric aerosol emission estimates show that for sulphur injection frequency similar to Mount Pinatubo's eruption in 1991, extra-tropical eruptions produce more climatic variation in Northern Hemisphere 80% higher than the tropical volcanic eruptions (Toohey et al. 2019).

Table 1 Top ten major volcanism events in human history

Mountain name	Country	Century/Year	Losses
Mt. Tambora	Indonesia	April, 1815	120,000 people
Krakatoa	Indonesia	August, 1883	36,000 people
Laki	Iceland	1783	10,000 in Iceland 23,000 in Great Britain and caused famine in Egypt
Mt. Pelee	Caribbean	May, 1902	28,000 people
Ilopango	El Salvador	450 AD	Up to 100,000
Mt. Unzen	Japan	1792	15,000 people
Nevado del Riuz	Columbia	1985	20,000 people
Mt. Pinatubo	Philippines	June, 1991	722 people
Mt. Vesuvius	Italy	August, 79 AD	16,000 people
Santa Maria	Guatemala	1902	5000 people

Source https://www.australiangeographic.com.au/topics/science-environment/2017/01/the-worlds-10-most-devastating-volcanic-eruptions/

Whether large volcanoes in the northern hemisphere and southern hemisphere have distinctive impacts on the monsoon is uncertain. Using Group Earth System Model 1.0 (CESM1) 1500-year volcanic susceptibility simulation, we fix this problem. Volcanoes are classified into three northern hemisphere volcanoes, southern hemisphere volcanoes, and equatorial volcanoes. Using simulation, we notice monsoon precipitation in one hemisphere is significantly enhanced by remote volcanic forcing in the other. This remote forced volcanic intensification is primarily attributed to shifts in circulation rather than moisture content.

Volcanic eruptions in the northern hemisphere are more effective in decreasing monsoon precipitation in the northern hemisphere than in the equatorial ones. So are the southern hemisphere eruptions in weakening the monsoon in the southern hemisphere, as tropical eruptions have weaker results in cutting off-equatorial moonsoon circulation, thus decreasing humidity (Liu et al. 2016). Volcanism originated aerosols alter the climate at local or regional scales via their interaction with clouds. Volcanism at larger scales releases sulphur dioxide (SO_2), which is the primary precursor of aerosols and controls atmospheric interactions. Based on the Holuhraun eruption in Iceland during 2014–15, it has been shown that the eruption released pollutants have the potential to influence the climate at local levels (Malavelle et al. 2017).

3.1.2 Ocean Circulations

Changes in oceanic heat transport may lead to repeated or cyclic alterations in temperature. During the glacial periods between 25,000 and 60,000 years, scientists explored the high-resolution atmospheric and oceanic circulations in the deep North Atlantic ocean and predicted the reduced overturning of Atlantic oceanic circulations during each cold age indicating that oceans play a pivital role in abrupt glacial climate shift (Henry et al. 2016; Lynch-Stieglitz 2017).

Trossman et al. (2016) assessed interactions between CO_2-forced ocean circulation disruptions and clouds in a prediction model and observed that both the factors, significantly influence the surface and ocean heating. Due to the change in ocean circulations, cloud feedback is very crucial in controlling southern heat flow. It is the primary feedback mechanism that reacts in response to the ocean circulations. He et al. (2017) attempted a study to know about variabilities and how they are related to the baseline environment simulations by comparing two input simulations in the same model and concluded that ocean circulations are slower and stronger at initial stages. Smaller reductions in poleward ocean heat flow results in less tropical ocean heat absorption and less surface warming as seen in both the hemispheres. But the changes in circulation overturning of southern Atlantic and Antarctic Bottom Water production dominate the warming differences in both hemispheres. This process is further enhanced by albedo and cloud input, causing a reduction in ocean heat absorption efficiency.

Important observational data suggests that extreme ocean warming is seen in response to change in currents near South Brazil and Río de la Plata. Changes in ocean circulation are responsible for poleward migration of fisheries in Uruguay's due to migration of fish species from cold-waters to warm-waters. Long-term experiments on ocean circulations and CC interactions suggests prolonged shellfish closures. Algal blooms and extreme weather events further impact coastal shellfish, native's income, and change in livelihood patterns of local communities (Franco et al. 2020).

3.1.3 Solar Variations

Solar flux is the fundamental energy source of the climate system on earth, and long-term climate change is significantly due to the earth's motion. Studies have pointed out that little climatic system variations may be aggravated due to variations in astronomy and earth movement factors. For example, air to sea feedbacks in cloud-free areas of the subtropical Pacific and tropical precipitation zones can increase solar impact mechanism on the Pacific climate system. This small change in the initial solar system can be further amplified by GHGs and CC (Xiao et al. 2017; Maclean et al. 2017).

Gathered and reconstructed data can be used for the examination of solar activity cycles. Data sources like sunspot number, Earth's climate change, Lake Qinghai temperatures in China, Vostok in Antarctica, Greenland's GISP climate record, and China's Dongge Cave stalagmite-18O moonsoon records can be used for this purpose. Earth's temperature index variations have been observed to show the 1000-year cyclicity, recently identified in solar activity (called the Eddy cycle). Cross-wavelet interactions between the elements of the millennium-cycle sunspots and Earth's climate shift stay strong and steady throughout the past 8640 years (BC 6755–AD 1885). The precise and reliable resonant relationships between sunspot numbers and these climate indices suggest that solar fluctuations may have played a role in modulating the Earth's climate change trend of the millennium before the new industrial revolution (Zhao et al. 2020).

3.1.4 Internal Variability in Climate

Natural climatic variability is one of the primary sources of uncertainty and leads to higher or lower than the projected CC trends. Many projections and experiments are performed to assess whether natural climate change influences the capacity to track mean and extreme precipitation. The mean indicators are annual and seasonal average precipitation, while the extreme indicators are the yearly and seasonal total regular precipitation. This is done with 50-member CanESM2 and 40-member CESM1 broad simulation sets over the period 1950–2100. Locally, their results suggest that natural temperature variability in some regions of the world will regulate uncertainty for annual and seasonal heavy precipitation before the end of the century. For combined precipitation (yearly and seasonal), the CC impacts can be detected accurately without using regional data. But climatic variations can add to the errors in detecting anthropogenic CC signals for mean and severe precipitation before the middle to late centuries (Martel et al. 2018).

Studies suggest that positive temperature difference from the medium-term mean, reflecting CC, affects Pakistan's farmland prices. Although the marginal impact estimates show a slight, yet negative linear association with farmland values. Conversely, the position of farms in regions where farmers may use financial or extension services has had a beneficial impact on agricultural prices, as has irrigation facilities (Arshad et al. 2017).

Areas of small, subtropical lakes are mostly susceptible to global warming-induced CC. Many rivers are on the cyclone strike line, with high inter-annual and inter-seasonal drainage and rainfall variability. In the shallow nutrient lake cycling, these two factors regulate water column interaction, which play a significant part in this cycling phase. This water column brightens the harmful algal bloom characteristics and dynamics like cyanobacterial harmful algal blooms.

3.2 Anthropogenic

3.2.1 Fossil Fuel Emissions

Fossil fuel burning introduces GHGs into the atmosphere which contributes to CC. Countries with strong domestic fossil fuel resources have experienced a significant increase in the demand for primary energy from fossil fuels. This condition indicates a tremendous threat to CC mitigation, leaving only two main mitigation measures: (i) hold fossil fuels in the ground; and (ii) introduce technologies about carbon capture and its storage in the sinks (Johnsson et al. 2019). CC related research has traditionally highlighted the questions about sourcing fossil fuel as global benchmark emission scenarios (i.e. scenarios that do not recognize additional climate policies) is constructed on the assumption of ample twenty-first century fossil fuel supplies. However, existing forecasts remain critically unpredictable, and emerging literature provides revised figures. Studies suggest that by the end of the century, global temperatures will increase up to 2 °C by 2100 (Capellán-Pérez et al. 2016).

3.2.2 Agriculture

Agriculture and the associated sectors have significant environmental impacts, including GHG emissions. Agriculture generates 25% of GHGs emissions. Because of fossil fuel use and soil organic carbon depletion, it contributes 23–44% of global CO_2 emissions. Therefore, there is a dire need to identify the climate-smart primary agricultural practices to mitigate CC. It is suggested that primary tillage with minimal soil disturbance and lower operations is a suitable environmental friendly approach for combating CC (Pratibha et al. 2019). CC adaptation techniques are expected to predict impacts of higher temperatures, differential precipitation rates and elevated CO_2 concentrations on crop yields and GHG emissions (He et al. 2018).

Methane, another strong GHG originateds from livestock, paddy fields and wetlands (Poulter et al. 2017) therefore becomes a significant component of CC (Varotsos et al. 2020). Wetland CH_4 emissions are the leading natural causes of the global CH_4 budget. As the second-highest GHG, CH_4 is strongly associated with climate feedback. However, IPCC's fifth assessment study did not comprehensively analyze wetland CH_4 feedback due to data shortages. Therefore, the degree to which future wetland expansion and CH_4 emissions will evolve and thus affect climate feedback is of significant concern. Under the Representative Concentration Pathway, climate change-induced shifts in boreal wetland scale and temperature-driven changes in tropical CH_4 emissions will surpass 38–56% of anthropogenic CH_4 emissions by the end of the twenty-first century. Wetland CH_4 feedback translates by the end of the twenty-first century into an increase in additional global mean radiative pushing from 0.04 to 0.19 $W \cdot m^{-2}$ (Zhang et al. 2017).

Human demand for livestock products has gradually grown over the past few decades, primarily due to dietary reforms and population increase, with significant environmental consequences. It is estimated that gross CH_4 emissions in 2014 were 97.1 million tons (MT) of CH_4 or 2.72 gigatons (Gt) of CO_2-Eq. (1 MT = 1012 g, 1 Gt = 1015 g) from ruminant livestock, comprising 47–54% of all agricultural non-CO_2 GHG emissions. It is also revealed that since the 1890s, ruminant CH_4 emissions have increased by 332% (73.6 MT CH_4 or 2.06 Gt CO_2-eq). Furthermore, findings indicate that livestock sector in drylands had a 36% higher emission intensity (CH_4 emissions/ km^2) than non-drylands in 2014, due to the combined effect of higher livestock population growth rate and low feed quality (Dangal et al. 2017; Tapio et al. 2017).

To satisfy growing demand for meat-rich diets, livestock numbers are also rising. Sustainability of this trend was questioned, and shifts in the world's future, such as climate change, making certain areas less common to livestock. Wild herbivorous and livestock rely primarily on nutrient chemistry or composition forage seeds. Nutrition is strongly associated with weight gain, milk production and reproductive health, and nutrition is the main decision-making factor in enteric CH_4 output. Protein forage gain also increased with the inclusion of nitrogen fertilizer. It decreased due mostly to high-temperature increases, likely due to mixture changes in plant selection, as well as shifts in phenology and physiology. This concludes and describes a significant input on climate change, where rising temperatures decrease grass nutrient value and increase methane production by 0.9% with a temperature rise of 1 °C, providing an additional climate-forcing impact. In North America, the large sections of Eastern and Central Europe and Asia, methane production is expected to rise across the high-emission scenario. There is a clear need for size, presence, cattle location, and heat stress characterization should be added in potential modelling work (Lee et al. 2017; Moeletsi et al. 2017).

Combined with CH_4, nitrous oxide (N_2O) is another primary GHG emitted by livestock by enteric fermentation and manure regulation. Due to rearing business, developing countries produce large amounts of CH_4 and N_2O (Forabosco et al. 2017).

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Beyond Climate Change: Impacts, Adaptation Strategies, and Influencing Factors

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Abstract Climate change is considered as one of the most severe and common environmental phenomena. This phenomenon has had the most damaging effects on the local-agricultural communities due to its impact on employment, income sources, and agricultural products. The livelihoods of more than half of the local poor communities depend on this sector and are hence more vulnerable to climate change. This issue is especially prominent in underdeveloped and developing countries. This chapter investigates the impacts of climate change to identify strategies for adaptation of local and agricultural communities to this phenomenon and to describe the influencing constructs on the acceptance of those strategies. The investigation has been completed in three stages, including identifying and explaining the most critical impacts of climate change, identifying and introducing methods for adaptation of local and agricultural communities to climate change, and identifying and introducing constructs affecting adaptation strategies' adoption. A documentary research method based on reviewing and analysing various studies around the world was adopted to delve deeper into the topic. The first stage analysis showed that endangering human health, reducing food security, aggravating water shortages, damaging vital infrastructure, cultural shocks, deviating from sustainable development goals, threatening the territorial integrity of the countries, increasing local–regional conflicts resources over common pool resources, increasing internal and external migration, intensifying droughts, and increasing poverty in local communities are among the most important impacts of climate change. The second stage investigation demonstrated that

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the adaptation strategies to climate change could be divided into economic/social management, water resources management, and crop management strategies. The third stage investigations showed that the socio-economic, natural, human, physical, institutional, psychological, and agricultural constructs are the most critical factors affecting adaptation to climate change. Some practical suggestions were also presented to increase the adaptation of future climate change.

Keywords Climate change · Impact assessment · Adaptation · Vulnerability · Adaptation strategies

1 Introduction

In recent years, climate change has been in the policy framework of many countries (Valizadeh et al. 2020; Karimi et al. 2018). Climate change refers to climate fluctuations, directly and indirectly, related to human activities and change the atmosphere's composition. It also refers to climate diversity observed over similar periods (Amos et al. 2015). Investigations show that the phenomenon of climate change is ranked first among the ten threatening human factors. Changing rainfall patterns and rising temperatures are the most critical signs of climate change besides the other negative impacts on the environment (Nicholls 2011; Aphunu and Nwabeze 2012). Local communities, which are considered one of the main producers of food globally, suffer the most losses from this issue (Thoai et al. 2018). The impacts of this phenomenon through changes in precipitation, temperature, and carbon dioxide can negatively affect food production systems (karimi et al. 2018). However, the complexity of the driving and aggravating factors and the entanglement of its negative consequences have made this phenomenon one of the main concerns of local agrarian communities worldwide (Campbell 2010). Further, the existence of various definitions of climate change makes its study more important because it will affect the stakeholder adaptation strategies and subsequent responses to climate change (Stoutenborough and Vedlitz 2014). In other words, understanding the impacts of climate change can lead to a better understanding of the climate resilience promotors at the local level (Maleksaeidi et al. 2015), besides identifying ways or strategies for actors to adapt to this phenomenon and awaring about the influencing factors of behavioural changes in this pathway. These processes can also provide planners with the information they need to adopt appropriate support policies for sustainable livelihoods and pave way for sustainable natural resource management, sustainability, and inclusive development (Valizadeh and Hayati 2021; Dessai and Sims 2010; Sherval and Askew 2012; Keshavarz abd Karami 2016; Yazdanpanah et al. 2015; Bijani et al. 2019). Therefore, the purpose of writing this chapter was to investigate the impacts of climate change, identify strategies for adaptation of local and agricultural communities to this phenomenon, and describe the influencing constructs on the acceptance of those strategies. The specific objectives to achieve this goal included the following:

- Identifying and explaining the most critical impacts of climate change;
- Identifying and introducing methods for adaptation of local and agricultural communities to climate change; and
- Identifying and introducing factors influencing the adoption of strategies for adaptation to climate change.

2 Research Methodology

This chapter is a documentary and analytical research that was done using the research and analysis of electronic and library resources. For this purpose, a systematic search approach was used to gather the necessary information from different sources including articles, books, technical reports, master's theses, doctoral dissertations, book chapters, etc. Various databases such as Scopus, Google Scholar, Springer & Kluwer, Sciencedirect: Elsevier, Taylor and Francis, Wiley Interscience, Nature, and Proquest were employed to retrieve the related resources. Searching for resources following specific goals was done in three stages, and in each stage, different keywords were applied in search engines. In the first stage, the keywords "climate change impacts", "climate change consequences", "climate change rebound impacts", "long-term impacts of climate change", "short-term impacts of climate change", "climate change impacts on local communities", "impact assessment of climate change", and "climate change side effects" were used to retrieve the resources. Retrieved resources were examined after the initial screen to identify and explain the most critical impacts of climate change. In the second stage, the keywords "climate change adaptation", "climate change adaptation strategies", "climate change adaptation solutions", "adaptation to climate change", "climate change mitigation strategies" and "climate change coping strategies" were employed to search the relevant literature. Similar to the first stage, the retrieved sources were reviewed after initial evaluations to identify the most critical strategies for climate change adaptation. In the third stage, the keywords "factors influencing adaptation to climate change", "adoption of adaptation to climate change", and "determinants of adaptation to climate change" were used to retrieve the relevant literature from different sources. The review of the retrieved resources led to identifying the most critical factors affecting the adoption of adaptation strategies to climate change. For more straightforward analysis and conclusion, the initial results of the second and third stages were categorized in the form of some general factors.

3 Impacts of Climate Change

A critical review in various climate change studies shows that this phenomenon affects almost all components of the living systems. Increasing incidences and severity of climate events affects the seasonal rainfall patterns, declines food production, loss of food distribution infrastructure, dwindling assets and livelihood opportunities, and endangers human health in rural areas. However, the impacts and consequences of climate change can be summarized as follows:

– *Climate change and human health*

The health of the world's population depends on the sustainability and performance of environmental and physical systems (Mohammadi-Mehr et al. 2018; Sabzali Parikhani et al. 2018), often referred to as the life support system. The world climate system is an integral part of this life support system (Karimi et al. 2021). In this regard, in the early decades of the twenty-first century, when the growing human impacts on the environment changed the Earth's geological, biological, and ecological systems, a wide range of environmental hazards for the human health has emerged on a larger scale (McMichael 2003). Climate change has some profound implications on human health and is recognized as the most significant public health threat in this century (Mpambela and Mabvurira 2017). However, these negative impacts are either direct or indirect (Myers et al. 2011). Direct effects on the health include living in unusual weather conditions (summer heatwaves or winter colds), increasing natural hazards (floods, hurricanes, and droughts), and increasing the production of some air pollutants and allergens (McMichael 2003). Prolonged exposure to high temperatures can cause heat stroke, heat syncope, heat exhaustion, and even death (Valizadeh et al. 2021; Myers et al. 2011). Natural disasters caused by climate change such as floods and droughts are often accompanied by anxiety, shock, depression, sadness, despair, numbness, aggression, sleep disturbance, interpersonal problems, post-traumatic stress disorder, drug use, and suicide. Besides, climate change-related heat waves increase aggression, homicide, suicide, spousal abuse, and hospitalization rates among those with underlying mental health problems (Gifford and Gifford 2016). The indirect impacts are due to the modifiers of the social system (such as migration, conflict, destruction of infrastructure, and destruction of crops) and environmental elements (such as food, water, soil, and air) (Myers et al. 2011). Through indirect mechanisms, climate change can affect the transmission of many infectious diseases and reduce food productivity (McMichael 2003). Also, damage to basic infrastructure leads to population displacement and contamination of drinking water by sewage and runoff. Severe runoff from rainfall can also contaminate recreational water, and the number of bacteria in these places will increase the human disease risks (Myers et al. 2011). In general, the pathways through which climate change affects human health include the local modulating influences and the feedback impact of adaptation measures (Fig. 1).

– *Climate change and food security*

Food security has a broad and complex meaning and is determined by the interaction of biological, economic, social, physical, and agricultural factors. This issue can be addressed more efficiently by considering the food availability, food access, and food stability (World Bank 2001). Despite extensive efforts for sustainable development

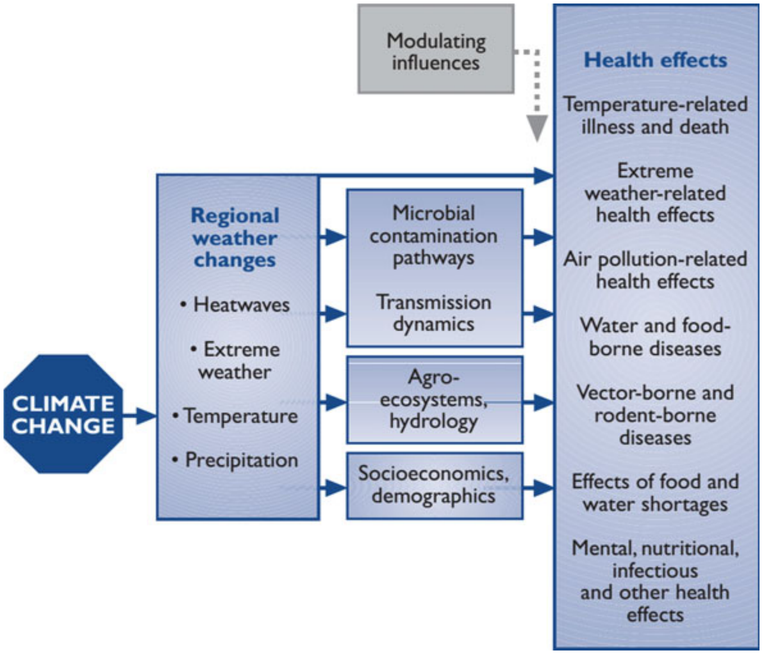

Fig. 1 Pathways by which climate change affects human health included local modulating influences and feedback influence of adaptation measures (McMichael 2003)

at the international level, the United Nations continues to call for food security as one of humanity's most significant challenges (Stephens et al. 2018). Since incoherent and incomplete food security is a big challenge, it will not be solved in the coming decades because climate change will have profound and direct impacts on agricultural and food systems over the next few decades (Brown and Funk 2008). Climate change will be one of the significant threats to food security in developing and underdeveloped countries. It will affect the agricultural and livestock sectors directly and indirectly on many aspects (Masipa 2017). The IPCC report shows that one of the most severe consequences of climate change is an increase in the number of people suffering from malnutrition because of the adverse impact of climate change on global agricultural production (IPCC 2007). Climatic conditions have always been a challenge for farmers, as the agricultural sector is more vulnerable to climate change, which directly affects countries' economic activity and increases the risk of hunger and malnutrition (Masipa 2017). Meanwhile, most studies on the impact of climate change on food security is focused on a single dimension of food security, i.e., food production (availability). Its impact on other aspects of food security (access, use, and stability) has not been considered. However, climate change affects food security's four major dimensions: availability, accessibility, stability, and use (Edame et al. 2011). Food security worldwide is at risk due to climate change and declining yields of key crops (Bocchiola et al. 2019). According to the IPCC, climate change can reduce food yields in parts of Africa by 10 to 20 per cent (IPCC 2007). Higher temperatures, reduced rainfall, and increased rainfall diversity reduce crop yields and threaten food security of low-income and agricultural economics (Deressa et al. 2011). Climate change directly affects agricultural and food products' availability due to its effects on crop yields, pests and diseases, soil fertility, and water quality. It also affects economic growth, income distribution, and demand for food and agricultural products. Climate change harms crop yield stability and physical, economic, and social access to foods. In nutshell, climate change would reduce agricultural production, increase food prices, and reduce the purchasing power of vulnerable and poor households (Edame et al. 2011).

– *Climate change and water resources management*

Water is a fundamental and strategic resource for socio-economic development and conservation of the environment in all its forms (rain, aquifers, streams, ponds, springs, lakes, rivers, oceans, and snow) (Valizadeh et al. 2020). However, water scarcity, water quality decline, floods, and droughts are the challenges that can be exacerbated by climate change (Urama and Ozor 2011; Estrela et al. 2012). In the climate change matrix, water resources are at the centre stage of exploitation. In other words, the impact of climate change on water resources will shortly become more apparent than predicted (Kusangaya et al. 2014). The effect of climate change on the availability and quality of freshwater has made water a top priority for countries (Safonov et al. 2019). Water resources are sensitive to the changes in climate pattern. It is believed that due to climate change, there are changes in water resources as climate change leads to increased runoff. However, due to suppression of evapotranspiration, it leads to an increase in CO_2 concentration (Singh et al. 2014). It is also notable that climate change has increased water stresses and conflicts by reducing runoff (mainly in the Mediterranean region, some parts of Europe, Central and South America, and South Africa). In some other water scared areas, such as South and East Asia, climate change is increasing the runoff. However, these increases are generally not helpful because they occur during the wet seasons. In other words, excess water may not be available in the dry seasons when needed (Estrela et al. 2012). Warmer temperatures can affect water quality in several other ways, including decreasing dissolved oxygen levels, increasing water pollution, reducing river flow, increasing algal blooms, and increasing the likelihood of saline infiltration near coastal areas. Acid rain is another primary reason for the disturbance of water quality due to the addition of sulphur and nitrogen compounds into it. Further, the changes in water flow characteristics intensify the transfer of chemical loads into rivers (Singh et al. 2014). Climate change is recognized as one of the most severe threats to groundwater, which is expected to affect the hydrological processes such as precipitation and evapotranspiration specifically. These processes can have a direct impact on surface water flow and recharge of groundwater aquifers and thus increase the water storage potential of reservoirs and groundwater aquifers (Valizadeh et al. 2021; Tesfahunegn and Gebru 2020).

– *Climate change and vital infrastructure*

Since the second half of the twentieth century, the economic damage of natural disasters related to climate change, including floods and droughts, has increased manifolds (Safonov et al. 2019). Climate models predict that by 2050, climate change will reduce agricultural land productivity by 10 to 20% in many developing countries. It has a significant impact on the agricultural sector, affecting 10% of agricultural lands. Accordingly, the farming households dealing with reduced crop production or reduced yield need to be supported. Otherwise, these changes will affect their livelihoods and increase their vulnerability to sudden changes (Gouda 2020). In recent decades, floods have accounted for almost a third of the economic damage caused by natural disasters worldwide and this damage has been mostly related to the welfare of communities and infrastructures. Another factor in the destruction of infrastructures is the melting of polar icecaps due to rising temperatures. As the catastrophe strikes, nearly three-quarters of the Arctic population will be at risk, and this will be specially important for Russia. The damage to the country's infrastructure (roads, gas and oil pipelines, heating networks, buildings, power lines, etc.) will increase manifolds (Safonov et al. 2019).

– *Climate change and culture*

Human beings look at nature through the lens of their beliefs, knowledge, and goals. In other words, their behaviour is based on their perceptions of nature and not on the actual structure of nature (Thomas et al. 2019). Environmental events put long-term and cumulative pressures on human life that can ultimately lead to cultural shocks. Cultural shocks are events or situations that cause a rift in "common ways of acting or thinking". Cultural damages and shocks are social processes that lead to the disruption of systematic cultural foundations and existing social orders. Climate change is thus a profound challenge to global lifestyles and the emergence of growing cultural damage (Brulle and Norgaard 2019). When the storm hit a poor community in a developing country on Mexico's Yucatan Peninsula, women deaths were three to four times more than men. This lethality rate is interpreted very differently to some extent by differences in learning and expected behaviour of men and women (Thomas et al. 2019). Culture and its analysis play a key role in understanding the causes, concepts, and human responses to climate change (Nail et al. 2013).

– *Climate change and the Millennium Development Goals (MDGs)*

Climate change is one of the severe threats to the sustainable development goals in various dimensions of environment, human health, food security, economic activities, natural resources, and infrastructure (Keshavarz and Karami 2014). Table 1 shows the impacts of climate change on the MDGs, which can be a significant obstacle to sustainable development (United Nations 2004).

Table 1 Potential impacts of climate change on the MDGs

MDGs	Chains related to climate change
Eradication of poverty and hunger	– Climate change is affecting people's livelihoods – It affects economic growth by destroying natural areas and reducing production. The slowdown in economic growth also has a direct impact on people's incomes – By reducing food production, it exacerbates food insecurity, especially in Africa
Access to basic education	– Climate change leads to forced migration and lack of time. This also limits educational opportunities for individuals and children
Gender equality and women's empowerment	– Climate change is exacerbating gender inequality. The depletion of natural resources and the reduction of agricultural production may endanger women's health. This can also reduce the time it takes for them to participate in decision makings
Goals related to health, combating important diseases, reducing child mortality and maternal health	– Climate change is leading to an increase in heat-related deaths and heat-related diseases – The increased prevalence of diseases such as malaria, cholera, and dysentery due to reduced quality of drinking water and food are the most important consequences of climate change
Ensuring sustainable development	– Climate change reduces the quality and efficiency of natural resources and causes irreversible damage to the ecosystems. It also reduces biodiversity and destroys the environment
Global partnership	– Climate change is a global concern and requires global partnership and accountability. This cooperation is essential for helping developing countries to adapt to the harmful impacts of this phenomenon

Source (McGuigan et al. 2002)

– *Climate change and territorial integrity*

Most of the negative impacts of climate change can be observed in areas such as the Eastern and Central Africa, the Middle East, Central and East Asia, which are the scene of many armed conflicts (Hegre and Sambanis 2006). The impacts of climate change could strengthen opposition groups in a country and thereby threaten the countries' territorial integrity. In 1970, a devastating tornado struck Bangladesh (then ruled by Pakistan) and the blatant contributions of Pakistani leaders accelerated the formation of the Bangladesh separatist movement, leading to war and conflict and Bangladesh's subsequent independence from Pakistan (Kolmannskog 2008).

Besides, one of the most important causes of Darfur tensions has been soil erosion and desertification. Because rainfall in this area decreased by 30% and millions of hectares of land in the area turned into a desert (Paskal 2007).

– *Climate change and local–regional conflicts resources over common pool resources*

The occurrence of climate change phenomenon that is formed due to reduction and lack of rainfall and relatively stable temperature changes in an area causes a decrease in groundwater and surface water levels and a water crisis (Karimi et al. 2018). The water crisis is exacerbating local, regional, and international conflicts over water. In recent years, conflicts have intensified in parts of the world that have experienced water crises due to climate change impacts such as droughts or severe water shortages. These conflicts show that climate change and its negative consequences, namely unemployment and poverty, exacerbate local and regional conflicts (Madani and Zarezadeh 2014).

– *Climate change and migration*

One of the most catastrophic impacts of climate change is migration. The number of migrants is increasing due to natural disasters related to climate change (Kolmannskog and Council 2009). In 2008, 42 million people were forced to migrate and relocate due to wars and conflicts caused by climate change (UNHCR 2008). Studies show that there were 25 million environmental migrants in the world in 1995, and the number of environmental migrants is projected to reach 250 million by 2050. The number of immigrants will further increase ten times (Myers 2002).

– *Climate change and drought*

Empirical evidences show that countries are more vulnerable to climate change induced droughts. Over the past decades, drought, one of the manifestations of climate change, has become more prevalent in arid and semi-arid countries and has posed a severe challenge to the communities (Keshavarz et al. 2013; Keshavarz and Karami 2014). One of the most essential consequences of these droughts is desertification, which is the third major challenge for the international community climate change and freshwater scarcity. Prolonged droughts can increase the risk of desertification due to countries' fragility in predominantly desert and semi-desert climates (Reynolds 2008). Another rebound effect of climate change-related droughts is the dust storms. In many parts of the world, rain and dampness in the soil cause soil cohesion. Prolonged droughts or uncontrolled use of surface water resources by upstream areas cause water loss and drying of wetlands, swamps, and plains and provide the basis for dust storms (Jacob and Winner 2009). For example, the continuation of droughts and drying of rivers and lakes have greatly impacted the intensification of dust storms in Iran (Karimi et al. 2017).

– *Climate change and poverty in local communities*

The predominant livelihood of villagers and agrarian communities is tied to agricultural and livestock activities (Keshavarz et al. 2013). Climate change is primarily destabilizing these essential livelihood source for rural society. Lack of water and the destruction of agricultural lands and pastures cause a sharp decline in rural income and create hidden and observable unemployment waves (Karimi et al. 2017). In recent decades, climate change has led to the complete evacuation of some villages and forced migration of villagers to neighbouring cities or metropolises in different countries. The severity of the impacts of climate change has been such that many of this phenomenon's negative consequences remain irreparable and have caused heavy damage to rural communities (Zobeidi et al. 2016). Together, this phenomenon is destroying the livelihoods of villagers, drastically reducing their purchasing power, and exacerbating the poverty. Also, the migration to cities and metropolises and the lack of jobs in new destinations increases the unemployment rate and the prevalence of slums and false jobs (Maleksaeidi et al. 2015).

4 Climate Change Adaptation Strategies

Modification in socio-economic and ecological systems in response to real or expected climate impacts and stimuli is called adaptation to climate change (Plummer et al. 2013). Adaptation features and behaviours of the system can increase the ability to cope with external stresses. Adaptation involves responding to a shock created by man or nature. This response can occur before, during, or after the event and contribute to the sustainability or improvement of socio-ecological systems (Renaud et al. 2010). Studies show that local and agricultural communities in different geographical areas use a wide range of adaptation strategies, e.g., Vietnamese farmers use strategies such as changing crops, cultivation methods, and planting calendar to cope with climate change and drought (Ngo 2016), indicating that the experience of hazards is the most important determining factor in dealing with these natural phenomena. Similarly, the adaptation of local institutions to climate change using an agent-based modelling approach by Wang et al. (2013) showed that the livestock livelihood strategies in Mongolia and China are very different. Social participation was one of the livelihood adaptation strategies observed in Mongolia. Local institutions, including the government, the market, and social institutions, play an important role in shaping and facilitating adaptation to climate change and livestock farmers' livelihoods. Forage storage, diversification of livelihood resources, and different markets were three categories of adaptation strategies in central Mongolia. The adaptation strategies in these groups were mainly formed with government and local institutions' support. While pointing to the impacts of drought in the Herat region of Afghanistan, Iqbal et al. (2018) pointed out that farmers interpret climate issues based on their religious beliefs. However, they perceive drought as a climatic and environmental phenomenon based on rising temperatures, declining rainfall, overuse of groundwater, financial weakness, pasture degradation, and deforestation. Analysis of farmers' readiness and adaptation measures in Herat also show that low education, low income, and tendency to rely on off-farm income sources have led to passive adaptation measures and short-term response strategies. From Pakistani farmers' perspective (Fahad and Wang, 2020), factors such as reduced soil fertility, water scarcity, change in crop yields, and plant diseases are indicative of climate change and drought. Their solution to these fluctuations was to change the type and variety of crops, and fertilizers improve the quality of seeds and toxins, store water. However, these farmers faced serious constraints along the way, such as labour shortages, lack of market access, poverty, lack of government support, lack of water resources, lack of credit resources, and lack of knowledge and information. In Tanzania (Below et al. 2012) the coping strategies are classified in three categories, including water management in agriculture (12 adaptation strategies), farm and farm management adjustment (12 adaptation strategies) and diversification outside of the farm (9 adaptation strategies). Agricultural water management strategies include changing the irrigation system, building ponds and canals, planting cover crops, deep tillage, hedge, appropriate irrigation, mulching, co-irrigation, and irrigation pumps. Crop management strategies include afforestation, use of organic livestock manure, use of mineral fertilizers, crop rotation, climate change resistant crops (e.g., sorghum, millet, peanuts, sunflower), expansion of agricultural lands outside of the area, expansion of agricultural lands within the sector/area, planting vegetables in the off-season, keeping livestock, intercropping, and planting species with shorter lifespans. Off-farm strategies include crafts, trade, natural resources (wood, charcoal, fish, and minerals), rental of property and belongings, professional occupations, technical expert, temporary migration, and traditional medicine/treatment. Here the adaptation strategies are considered as a function of farmers' perceptions of climate change, social, and economic characteristics of the household (wealth, education, work experience, age, membership in social groups, number of dependents, the gender of the head of the household, financial capital, and productive assets), farm characteristics (land ownership and soil fertility), institutional frameworks (access to agricultural extension services), and infrastructure (market access). In Bangladesh, the rural households perceive and understand (Alam et al. (2017) the profound impacts of climate change on their resources and livelihood, leading to an increase in their vulnerability. Therefore, households used a wide range of agricultural and non-agricultural strategies such as cultivating new crops, changing planting times, focusing on planting garden crops, and migration to adopt to such changes. Improving access to financial support and information on appropriate adaptation strategies at the local level improves vulnerable households' resilience. The drought coping approaches and adaptation strategies (Speranza 2010) for adapting the ranchmen to Kenya's drought impacts, where inadequate nutrition and livestock diseases were the most important challenges for one-third of ranchmen families during periods of drought. Ranchmen responses to the drought period mainly included the intensification of rangeland use. Therefore, less attention was paid to improving rangeland quality. The dependence of many livestock ranchmen on their livestock was one of the main reasons for not selling livestock in drought conditions, and this caused financial losses to these households. Providing developmental services, maintaining infrastructure, ensuring the safety of livestock movement, and sustaining pastures were considered appropriate strategies for coping with drought. In general, Table 2 shows the most important strategies chosen for an adaptation to climate change, extracted using a literature review and then classified into several categories.

Table 2 Climate change adaptation strategies

Category	Adaptation strategies	Number of studies	Sources
Economic/social management	Buying and selling agricultural land	3	Wheeler et al. (2013), Below et al. (2012), Mertz et al. (2009)
	Selling of agricultural water	2	Wheeler et al. (2013), Keshavarz et al. (2013)
	Job diversity	3	Below et al. (2012), Speranza (2010), Wang et al. (2013)
	Leasing agricultural lands	2	Below et al. (2012), Osbahr et al. (2008)
	Crop-livestock insurance	2	Karimi et al. (2017)
	Migration	2	Zhang et al. (2013), Karimi et al. (2017)
Water resources management	Buying extra water	2	Wheeler et al. (2013), Below et al. (2012)
	Improving the irrigation system	5	Wheeler et al. (2013), Keshavarz et al. (2013), Below et al. (2012), Urquijo and De Stefano (2015)
	Dredging rivers and canals	2	Keshavarz et al. (2013), Urquijo and De Stefano (2015)
	Water storage (pool construction)	2	Keshavarz et al. (2013), Below et al. (2012)
	Well digging	3	Keshavarz et al. (2013), Below et al. (2012), Urquijo and De Stefano. (2015)
	Excavation of wells	3	Keshavarz et al. (2013), Below et al. (2012), Urquijo and De Stefano. (2015)
	Change the area under cultivation	3	Wheeler et al. (2013), Keshavarz et al. (2013), Ngo (2016)

(continued)

Table 2 (continued)

Category	Adaptation strategies	Number of studies	Sources
Crop management	Changing the cultivation pattern	4	Wheeler et al. (2013), Keshavarz et al. (2013), Karimi et al. (2020), Urquijo and De Stefano (2015)
	Crop rotation	3	Keshavarz et al. (2013), Below et al. (2012), Alam (2017)
	Crop diversity	7	Wheeler et al. (2013), Keshavarz et al. (2013), Below et al. (2012), Mertz et al. (2009), Bryan et al. (2009), Ngo (2016)
	Planting drought tolerant species	3	Keshavarz et al. (2013), Below et al. (2012), Ngo (2016)
	Changing planting date	3	Keshavarz et al. (2013), Bryan et al. (2009), Ngo (2016)
	Planting high yielding species	2	Karimi et al. (2017), Wang et al. (2013)
	Use of fertilizers and pesticides	2	Keshavarz et al. (2013), Below et al. (2012)
	Soil protection (protective plowing, mulching, and so on)	4	Keshavarz et al. (2013), Below et al. (2012), Bryan et al. (2009)
	Land leveling	1	Keshavarz et al. (2013)

5 Factors Influencing Adaptation to Climate Change

In addition to the adaptation strategies, some factors facilitate the adoption of adaptation strategies in the face of climate change. Therefore, at this stage, the most important of these factors were extracted and categorized using literature review and analysis of previous studies. Like adaptation strategies, many studies have been conducted on the factors affecting the adaptation of rural and agricultural communities to climate change. However, since these studies have been conducted in different times, places, and communities, the results of many of them are not generalizable. In this regard, first, some of these studies are mentioned, and then their results about factors affecting the adaptation of local communities and agriculture to climate change are combined. Dang et al. (2014) showed that in Vietnam's rice farmers the socio-economic factors and the availability of resources affect their adaptation and decisions in response to climate change. When these farmers perceived a higher probability of loss from climate change, they were more likely to develop adaptive behaviours. Farmers were also more adaptable when they had a greater understanding of climate change consequences or when they were pressured to adapt by other people (social environments). It showed that the protection motivation theory is a useful framework for understanding farmers' intention to adapt and behave in response to climate change. Habiba et al. (2012) stated that in drought adaptation in northern Bangladesh the farmers believe that changes in rainfall and temperature cause drought. They further believe that declining groundwater and surface water, increasing demand and poor water management approaches, increasing population, and deforestation exacerbates the drought. Factors affecting farmers' adaptation to drought included agricultural management practices, crop diversity, exploitation of new water resources, and the use of new technologies. Similarly, the Pakistani farmers (Ashraf and Routray 2013) consider the drought as a result of religious beliefs, rising temperatures, decreasing rainfall, changing rainfall times, improper use of groundwater and population growth. They used agricultural and non-agricultural strategies to deal with drought. Iranian farmers' adaptation to climate change (Keshavarz et al. (2013) based on principal component analysis and fuzzy logic is classified into three categories: low, medium, and high. This classification was based on the farmer household's adaptive capacity and sensitivity and the agricultural exploitation system. Adaptation capacity included social, physical, natural, financial, and human capitals, and the sensitivity of the agricultural exploitation system depended on the natural resources and livelihood of the family. Factors influencing adaptation include crop management, water harvesting, crop enhancement, income diversity, and cost management. In general, (Table 3) the most important constructs affecting adaptation to climate change in agricultural communities, was classified into several categories.

6 Conclusion and Recommendations

The world's climate is changing, and this change continues at an unprecedented rate in the contemporary times. Climate change can be considered one of the severe issues that threaten sustainable development in terms of environment, human health, food security, economic activities, natural resources and infrastructure. Meanwhile, underdeveloped and developing societies' dependence on the climate causes these societies to be significantly affected by this phenomenon. Therefore, if sustainable development is one of the central policies of countries with economies based on natural resources, they should reduce the vulnerability of agriculture and livestock sectors to climate change. It should be noted that the agricultural and livestock sectors are more vulnerable to climate change than the industrial and services sector. In this regard, factors affecting adaptation to climate change and strategies for adapting these sectors to climate change are essential. Also, pursuing this goal in climate change research is done not only to select the best policy to reduce the change but also to provide solutions to reduce the vulnerability of these groups and thus reduce the inevitable costs. Therefore, this study aimed to identify adaptation strategies

Table 3 Factors influencing adaptation to climate change

Factor	Influencing variables	Number of studies	Sources
Economic	Number of employed family members	3	Keshavarz et al. (2013), Below et al. (2012), Karimi et al. (2017)
	Household income	5	Keshavarz et al. (2013), Below et al. (2012), Mary and Majule (2009), Karimi et al. (2017), Bryan et al (2009)
	Household savings	5	Keshavarz et al. (2013), Below et al. (2012), Mary and Majule (2009), Karimi et al. (2017), Bryan et al. (2009)
	Livestock-farming crop insurance	2	Keshavarz et al. (2013), Karimi et al. (2017)
Social	Impact of reference groups	3	Dang et al. (2014), Wang et al. (2013), Melka et al. (2015)
	Intra-group communication	4	Keshavarz et al. (2013), Below et al. (2012), Karimi et al. (2017), Wang et al. (2013)
	Extra-group communication	3	Keshavarz et al. (2013), Below et al. (2012), Wang et al. (2013)
Natural	Soil fertility	3	Keshavarz et al. (2013), Below et al. (2012), Bryan et al. (2009)
	Water and soil quality	3	Keshavarz et al. (2013), Habiba et al. (2012), Wheeler et al. (2013)
	Agricultural water	4	Keshavarz et al. (2013), Karimi et al. (2018), Wheeler et al. (2013), Pandey et al. (2015)
Physical	Farm size	5	Keshavarz et al. (2013), Below et al. (2012), Wachinger et al. (2013), Butler et al. (2014)
	Number of livestock	3	Keshavarz et al. (2013), Karimi et al. (2017), Speranza et al. (2010)
	Characteristics of irrigation and agricultural systems	2	Keshavarz et al. (2013)

(continued)

Table 3 (continued)

Factor	Influencing variables	Number of studies	Sources
Human	Education	5	Keshavarz et al. (2013), Below et al. (2012), Plummer et al. (2013), Wachinger et al. (2013)
	Age	5	Keshavarz et al. (2013), Below et al. (2012), Karimi et al. (2017), Wachinger et al. (2013)
	Knowledge about climate change	4	Mary and Majule (2009), Marin (2010), Pandey et al. (2015), Plummer et al. (2013)
Institutional	Access to extension services	4	Keshavarz et al. (2013), Below et al. (2012), Bryan et al. (2009), Melka et al. (2015)
	Access to markets	3	Below et al. (2012), Karimi et al. (2017)
	Access to climate information	3	Karimi et al. (2018), Bryan et al. (2009), Pandey et al. (2015)
	Access to facilities and credits	5	Keshavarz et al. (2013), Bryan et al. (2009), Bryan et al. (2009), Zhang et al. (2013), Wang et al. (2013)
Psychological	Fatalism	4	Dang et al. (2014), Zobeidi et al. (2016), Wachinger et al. (2013), Ashraf and Routray (2013)
	Perception of climate change risk	6	Dang et al. (2014), Below et al. (2012), Mertz et al. (2009), Mary and Majule (2009), Wachinger et al. (2013), Frank et al. (2011)
	Attitudes towards climate change	8	Dang et al. (2014), Wheeler et al. (2013), Melka et al. (2015), Ashraf and Routray (2013), Simonsson et al. (2011), Carlton et al. (2016), Alam et al. (2017), Udmale et al. (2014)
Agricultural	Type of cultivation (spring/autumn)	4	Keshavarz et al. (2013), Ngo (2016), Wheeler et al. (2013)
	Pest prevalence	2	Keshavarz et al. (2013), Fahad and Wang (2020)

(continued)

Table 3 (continued)

Factor	Influencing variables	Number of studies	Sources
	Drought damage rate	3	Keshavarz et al. (2014), Maleksaeidi et al. (2015), Karimi et al. (2018)

and factors affecting the adoption of these strategies to reduce the vulnerability of communities to climate change. But before focusing on adaptation strategies and the factors affecting it, an attempt was made to introduce the most important impacts of climate change in the world including endangering human health, reducing food security, aggravating water shortages, damaging vital infrastructure, cultural shocks, deviating from sustainable development goals, threatening the territorial integrity of the countries, increasing local–regional conflicts resources over common pool resources, increasing internal and external migration, intensifying droughts, and increasing poverty in local communities. Further, reduced food security, endangered human health, increased poverty, and migration are the most important impacts of climate change, especially in agricultural and rural communities. So, the policy-makers and decision-makers reduce communities' vulnerability to climate change by focusing more on these impacts.

One of the best ways to reduce these impacts is to hold training and enlightenment courses on the importance of agricultural and rural production systems compatible with climate change in achieving food security. Besides, educators and practitioners of these courses should emphasise ways to diversify agricultural and rural activities under the climate change. The reliance of villagers and farmers on a single source of income increases their vulnerability. They should be encouraged to use different sources of income concerning their specific conditional factors. Government support such as the guaranteed purchase of manufactured products and countering the import of foreign products (which prevents the sale of products produced by agricultural and rural communities) can be as facilitating factors in this regard. Taken together, these measures can reduce poverty and reduce the spread of poverty in rural and urban communities.

This study divided climate change adaptation strategies into three categories of socio-economic, water management, and agricultural strategy. The first category (socio-economic) included buying and selling agricultural land, selling agricultural water, job diversity, leasing agricultural lands, crop-livestock insurance, and migration. Given that in the agricultural and rural communities, collective wisdom and social pressure are one of the main drivers of farmers' decision to use strategies to adapt to climate change. It is recommended that managers and implementers of climate change mitigation programs pay more attention to the existing social capital such as formal/informal local institutions and organizations. In situations where such organizations do not exist, intervenors can create them as a first step to pave way for the planned changes through socio-economic strategies. Such measures should be taken at the same time as providing facilities such as agricultural loans, subsidies, distribution of medicines and subsidized fodder, construction of residential centres, water supply to vulnerable areas, restoration of pasture flora and fauna, training classes, and guaranteed purchase of products by the government. The second category of climate change adaptation strategies was water-related strategies such as buying extra water, improving the irrigation system, dredging rivers and canals, water storage (pool construction), well digging, excavating wells and changing the area under cultivation. The implementation of these solutions should be done in two steps. The first phase involves behavioural intervention in water use optimization methods (such as improving the irrigation system and dredging rivers and canals) in the agricultural and rural community. At this stage, farmers and villagers are mentally prepared to accept water resources management measures. The second phase involves the technical and financial support of farmers and villagers to implement the methods. This step is to ensure the correct implementation of strategies and the sustainability of their use. The third category of climate change adaptation strategies related to crop management practices is changing the cultivation pattern, crop rotation, crop diversity, planting drought-tolerant species, changing planting date, planting high yielding species, use of fertilizers and pesticides, soil protection, and land levelling. Like strategies related to water resources management, its implementation requires two behavioural intervention stages and technical and financial support.

The third phase of the study divided the factors influencing the adaptation of farmers and villagers to climate change into economic, social, natural, human, physical, institutional, psychological, and agricultural. The experience of different countries (developed, developing and underdeveloped) shows that adaptation to climate change is closely related to each of these factors, and all these factors should be considered in a comprehensive approach. However, it should not be neglected that adaptation to climate change is generally a context-specific phenomenon. In other words, different combinations of these factors may have significant impacts in different regions. In this regard, it is suggested that before implementing any program to improve adaptation to climate change, the most critical factors affecting the adaptation of farmers and villagers be identified.

In general, this study suggests that any planning and intervention in adaptation to climate change requires three steps of identifying the impacts of climate change, presenting adaptation strategies, and understanding the factors influencing adaptation.

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Climate Change and Interconnected Risks to Sustainable Development

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Abstract The growing concern to improve on human condition and dignity constitutes governments' primary pursuit across the world. Conversely, this chase is accompanied by circumstances that are confronting the basis on which human survival depends. Amongst these conditions, 'climate change', caused by the escalating levels of greenhouse gases in the atmosphere is posing the practically significant impact on human progress. It undermines biodiversity's productive capacity, distorts hydrological balance, degrades soil nutrients, weakens agricultural production, impedes educational advancement and hampers human health's stability. These impacts are rife, with grave implications and have a multiplier effect. They lead to interconnected secondary consequences, which disrupt the synergies of sustainable development goals and worsen the climate challenge in a vicious cycle. The magnitude of these impacts is not felt proportionately in different regions. Besides their low economic status, developing countries are severely affected, and the existing gender norms and patriarchy undermine women and girls' disaster coping potentials. The consequences of these are inequality within and across nations, as well as intergenerational inequality. With the global temperature likely to keep rising, humanity is compelled in charting dynamic pathways of living with changing climate through mitigation and adaptation strategies. Unfortunately, most studies have addressed human goals in isolation, and there is infancy on the nexus of 'sustainable development goals' and interconnected risks associated with incremental global temperature. An in-depth understanding of the nexus that sustains human progress, the route through which climate change disrupts this nexus and integrating mitigation and adaptation approaches that strengthen this nexus' is required. This approach sets the pace for achieving environmental sustainability in ways that recognize local priorities, accommodate the vulnerable needs and ensure the well-being of the earth's people.

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1 Introduction

The unceasing quest to improve human well-being constitutes a preliminary plan for governments across the world. This reality has usually been at the expense of transforming natural resources to finished products for human consumption. In the mid-twentieth century, it became clear that the pursuit of global needs and aspirations is threatening the basis on which well-being relies (Meadows et al. 1972). Among these threats to human progress and well-being, global climate disruption is posing the most significant defiance to the environmental security of the earth and the heritage of future generations (Jafari 2013; World Bank 2016). Although natural occurrences such as variations in the earth's orbital characteristics, volcanic eruption, solar output variations, plate tectonics among others were observed to alter the global temperature, they are limited in their total contributions to global temperature changes (Eneji et al. 2017; IPCC 2018; Jafari 2013; Nwankwoala 2015). Thus, humans have remained the causative agent of the changing climate world.

Several reports from the 'Intergovernmental Panel on Climate Change' (IPCC) have confirmed and linked climatic perturbations to the rising human efforts and the eventual undue emissions of greenhouse gases that started during the industrialization era (IPCC 2018). This change in temperature of the planet stems from atmospheric retention of heat. When the suns radiations reach the surface of earth, they are both assumed into space and absorbed by the earth. On absorption of visible light (longer wavelength), the universe emits some portions of the trapped energy back into the thin air in the form of heat (shorter wavelength infrared radiations). In this natural process, the heat-trapping gases such as water vapours (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide absorb the reflected energy and disrupt the heat processes, thus making the earth warmer and conducive for life. Without this natural process, the earth would have been too cold (−18 °C) for the survival of human habitation and other myriad life forms. Unfortunately, due to anthropogenic activities there is an increasing emission of greenhouse gases including CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons), HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), SF_6 (Sulphur hexafluoride) that further reduces heat loss into outer space, thus making the universe hotter than expected, a scenario referred to as 'the greenhouse effect'.

According to archival data, the developed countries with their characterizing expeditious industrialization and associated manufacturing and consumption trends, emit roughly three-fourth of the cumulative greenhouse gases, e.g. in the twentieth century, developed countries, with only 15% of the world population, accounted for most greenhouse gas emissions (Wei et al. 2016). On the other hand, the lagging industrialization capacity of the developing nations with higher population figures limits the levels of GHG emissions accruing from them. By the year 2030, just over half of the total emissions will be contributed by the developing countries, mainly due to rising human numbers, needs, economic productivity and growth (Ward and Mahowald 2014). Following this growing concern, 194 countries agreed with the baseline evaluation in ratifying the 'United Nations Framework Convention for Climate Change' (United Nations 1992). Since then, there have been several international conferences and workshops to chart out a path on reducing emissions and assessing commitments.

Although several efforts geared towards reducing global emissions, and the concomitant rise in global temperature is still going on (Jafari 2013). Human activities have increased the global temperature by 1 ºC over the pre-industrial level, and with the current pace of warming, it is likely to reach 1.5 ºC between 2030 and 2052 (IPCC 2018). Vermeer and Rahmstorf (2009) have estimated that the changing temperature will cause global sea level to rise between 50 and 190 cm from the years 1990 to 2100, with grave implications on coastal communities. The consequences are rife and are already being felt, especially in developing countries, with wide-scale effects on our planet's sustainability due to adverse ecological, social and economic impacts (CRED and UNISDR 2017; Dale and Frank 2017). The improper management of these impacts leads to secondary effects which worsen the existing human suffering, degrade environmental health and exacerbate the climate challenge (Bradshaw and Fordham 2013; DESA 2017; Onwutuebe 2019).

For successful climate change mitigation, a holistic appreciation of the nexus that supports human society and how climate change disrupts the synergy is necessary (Cramer et al. 2018). Unfortunately, within the scope of the sustainable development plan, and the research that has deciphered about sustaining human progress and the interconnected damage to human development caused by climate change is still in its infancy. With the growing need to support human well-being and the diversity of flora and fauna, understanding the scope of interconnected risks associated with climate change and deploying trans-boundary and trans-sectoral adaptation and mitigation strategies to these risks have become imperative. These survival strategies are increasingly becoming a subject of importance in defining a safe corridor for humanity.

2 Human Goals in the Face of Changing Climate

2.1 Nexus of Human Goals for Sustainable Development

Achieving human progress requires a meticulous harmony of goals. Defining these goals and setting targets to measure achievements have become common at the international agenda (United Nations 2015, 2017). As the race towards sustainable development is becoming a daunting feat, the list of seventeen (17) UN Sustainable Development Goals, challenges the perception of human advancement (Hall et al. 2016; Liu et al. 2018). Rockstrom (2016), posits that human progress, as interpreted in the SDGs, could be achieved through a collaborative approach which handles the synergies and tradeoffs within different aspects. Thus, there is a need to reveal the dynamics of human progress imperatives as multi-consideration of the synergies would explore the interactions among sectors and deduce the peculiar implications of climate change as a driver of environmental change.

Tracks of nature reserves (biodiversity), water cycle, soil resources, agriculture, quality and improved education and health are associated nucleus of human need areas affected by climate change. These variables are aligned directly or interconnected to the seventeen SDGs' failure or progress (United Nations 2017). For example, in a conducive climatic condition (goal 13), soil health is maintained; watersheds are secured and the hydrological cycle is balanced (goals 14 and15) when the learning environment is conducive and healthy (goals 3 and 4); agricultural systems are productive and strengthen farmers' safety nets (goals 1 and 8). Increasing agricultural yields reduce hunger (goal 2), enhance human health and well-being (goal 3), empower farmers' ability to give quality education to their children and minimize school drop-outs (goal 4). Educational progress is aligned with technological progress which contributes to handling complex global challenges (goal 9), creates decent jobs, enhances economic growth and makes the world prosperous (goal 8). Better income and well-being for communities reduce intra and intergenerational inequality and international inequality (goals 5 and 10). A habitable climate will reduce climate-related disaster and makes our settlements more livable and sustainable (goal 11), guarantees a resilient economy, sustain clean water, enhance proper sanitation system and reduce health challenges (goals 3, 6 and 8). This will further reduce dependence on unsustainable energy sources for fans and air conditioning (goal 7).

Furthermore, the goals mentioned above are strengthened when there are robust institutions and governance systems (goal 16) that ensure effective citizen participation in decision-making. Externalities of commodities from the cradle to the grave are internalized into the cost of the entities (goal 12); resource sharing is objective; expression of goodwill for tomorrow; enhance gender parity (goal 5) and protects the vulnerable. Stable institutions are crucial for efficacious climate action to address climate change as they secure peace and sustainable development (UNFCCC 2020). Reliable institution per se require a holistic approach to handling all excesses that could arise from corruption and eventually jeopardize climate action attainment. With these approaches, the likelihood of protests which degenerate to conflict is minimized, and partnership at the domestic and international level is strengthened (goal 17). This behaviour yields a just, productive and a secure global feature.

Regrettably, when climate change inflicts, the system that sustains the progress is disrupted, degenerating to human suffering and degrading environmental health (Newman 2019; Nga 2020). The direct challenge of human needs (biodiversity, water, soil, agriculture, quality education and health) by climate change degenerates to interconnected secondary impacts and this relationship is characterized by a 'vicious cycle'. These impacts include insecurity, inequality, hunger, poor health, degraded living standards, disruption of settlements and infrastructure, loss of descent jobs and, increasing demand for unsustainable energy. Impeding educational progress and other areas of human life that fall within the ambits of issues under consideration by the sustainable development agenda (United Nations 2017) exacerbates the cycle.

2.2 Climate Change, Natural Resources and Risks to Sustainable Development

The abundance of life forms and environmental interaction are the core processes that sustain life on earth (Ricard 2014; Sintayehu 2018). These interactions provide shelter to some species, regulate temperature, clean air, freshwater, preserve and enhance soil nutrient, and the livelihood of the people living within the backyard of these resources (Langat et al. 2016; Ministry of Foreign Affairs of Finland 2013). While deforestation, for example, increases the concentration of atmospheric carbon and subsequently, global temperature, forest productivity also increases as a result of increased photosynthesis (Hickler et al. 2015). Unfortunately, the rise in temperature increases the risk of droughts, pests, fire, invasive species and other stressors, decreasing forest productivity (Dale and Frank 2017). As the temperature rises, the indigenous flora and fauna disappear with new species' emergence, while some animal species migrate northward (Sintayehu 2018). Some of the migratory species are facing the challenge of adapting to new environments. The presence of invasive species and other unknown pests bring new ill-health and add to the miseries of human health (Howard 2019). Furthermore, the warmer temperature has a feedback mechanism, following its capacity to hold more water vapour (a greenhouse gas) in the atmosphere, hence adding greenhouse gas concentrations (Held and Soden 2000; Sherwood 2009).

Increasing levels of atmospheric CO_2 and associated rising temperature of the planet is raising the temperature of aquatic environments, enhancing aquatic acidification, disrupting the coral shells building, habitat sabotage and disruption of the food chains (Colette 2018; Neelmani et al. 2019). These anomalies also increase the frequency of hypoxia and consequently offset the frequency of fish deaths, reduce wetlands coverage and the diversity of fish populations. A reduction in fish population affects the fishing industry's revenue, jobs, human food security and the productive and growing cycles of some species. When the seasonal abundance of fish sources fails to synchronize with migratory times, their survival is threatened (Mastrantonis et al. 2019). Increasing temperature affects groundwater recharge. Consequently, springs and small streams are drying up, reducing their potential of recharging wetlands. This deficiency leads to a drop in wetland coverage, lower water quality and a decrease in the diversity of aquatic life.

Climate change is also increasing precipitation in some regions of the world, and with dwindling vegetation cover, the frequency of flooding and erosion is increasing (CRED and UNISDR 2017). These conditions have resulted in the relocation of the residents of affected areas to safer zones, which exacerbates the existing land use impacts. While relocation to safer zones weakens traditional social networks, it creates more impervious surfaces, thus reducing the natural flood-absorbing capacities of wetlands, floodplains and natural vegetation. Increasing the risk of erosion and flooding has usually caused injury to people and the loss of human lives. Furthermore, erosion and flooding have been causing significant impacts on watersheds, potable water supplies, sanitation, ecosystems, agriculture, infrastructure, aesthetics of the environment and human well-being (Craighead 2017). After a flood event, for example, tangible and intangible losses occur. These tangible losses (e.g. clean-up cost, rental income from buildings, lower revenues and loss of jobs) and intangible losses (e.g. loss of human life, physical forms of injury, destruction of heritage sites) constitute a higher proportion of the GDP of the poor compared to the wealthy countries (CRED and UNISDR 2017; Hallegatte et al. 2016; Paprotny et al. 2018). The disruption of businesses and stoppage of production in the industrial and agriculture sector, for example, affects decent jobs, weakens households' economic stability and impedes economic growth. Furthermore, recurrent flooding in the emerging countries destroys national economies and frustrates efforts to accumulate tangible human capital, thereby wrecking the attainment of sustainable development.

The influence of climate change-related disasters is a universal catastrophe although there is a disparity in how it affects men and women in reality. Women and girls are more vulnerable to climatic disasters than men and boys (Hamidazada et al. 2019). This disparity in gender and vulnerability to disaster is more challenging in developing countries than in developed countries. In the wake of these disasters, women and girls have a higher chance of death than men (Bradshaw and Fordham 2013; DESA 2017), because due to socio-cultural and existing 'gender norms', these females have a limited access to resources. Likewise, they lag behind in the actual capacity to cope with climate change-related disasters, such as available information, education, health and wealth (land and infrastructures); hence their vulnerability is relatively higher than men. Following these losses suffered by women during disasters, they become more dependent on their male counterparts and are subjected to several induced impacts such as coercion and trauma, timely marriage pressure, limited educational opportunities and increased family workloads (USAID 2015).

Furthermore, patriarchy and the practice of preserving and transcending absolute values and assets in men's lineage is a common practice. Men are believed to be a sign of hope and sustainability of the family (Ajala 2017). As a result, women are marginalized at the degree of proprietary rights and access to land resources. Onwutuebe 2019 posits that male dominance over women on resource allocation accounts for a drop in women's ability to cope with climate change-induced perturbations. A significant proportion of women are involved in farming operations (Ezemonye 2015) a climate-sensitive livelihood. Their vulnerability to climate change-related shocks is relatively more significant than men. With their mainstay being inflicted, a reduction in income is being observed, putting them at risk of becoming extremely poor and vulnerable to poverty.

The poor are the primary group of people contributing the most harm to environmental quality (WCED 1987). Despite wide contestation on this opinion on poverty-environment nexus, the indigent is grossly trusting on natural endowments for livelihood and are engaged in unsustainable survival practices such as over-dependence on fuelwood for cooking, farming and settling on zones which weaken environmental resistance to disasters (Kassa et al. 2018; Khan et al. 2019). These practices increase CO_2 levels in the atmosphere, threaten their livelihood, weaken income, deteriorate health; thus worsening the climate challenge and well-being. In this regard, Nwagbara et al. (2012) and WCED (1987) claimed that no society can address sustainable development in isolation of the dual problems of poverty and environmental degradation.

The scale of climate change-related impacts affects the survival pathways of millions of people as it could cause national and regional insecurity. There is no significant correlation between climate change and violent hostility. However, existing conflicts in natural resource use may be exacerbated by climate-related factors, especially when society's economy is highly dependent on natural resources (SIDA 2018). Reducing access to water and extreme drought due to changing and threatening climate endanger food security and undermine households and communities' livelihoods. This leads to episodic events which are multifactorial and complex. These may embrace declining livelihood, increasing migration, changing pastoral mobility pattern, tactical considerations and exploitation by elites (Mobjork and van Baalen 2016). When people's livelihoods are being affected, it is believed that they stand to use the option of violence or joining some armed groups. As violent conflicts distort traditional social networks, people are forced to adopt unsustainable livelihoods. This results in perpetuating livelihood-conflict cycle, and worsening insecurity. Growing insecurity in a nation or region undermines the need to work together, reduce travelling and impede global partnership (United Nations 2017). Therefore, working in synergy is indispensable to combat the grievous climate change and enhance sustainable development.

2.3 Climate Change, Soils, Agriculture and Risks to Sustainable Development

Climate change reduces the capacity of soils and agricultural systems to sustain the increasing food needs of ever-increasing humans and other animals (FAO 2019). It disrupts the soil's nutrient balance, thereby degrading its quality to support food production (Brevik 2013; Kumar and Das 2014). Organic matter, an essential constituent of soil quality, gives it the structure and stability and ensures its water holding capacity. These organic matter characteristics enhance a suitable environment for microflora and fauna to thrive, making the soil productive (Eglin 2015). With the rising temperature, the organic matter is decomposed and lost as CO_2 to the atmosphere, while exacerbating the climate challenge and decreasing the productive capacity of the soil.

Furthermore, rising temperature, decreasing rainfall which subsequently leads to droughts in some region, thus resulting in increased groundwater dependency. In low lying coastal areas, increasing groundwater use for domestic, industrial and agricultural purposes further depletes the water table and allows saltwater to leach into the soil (Pulido-Bosch et al. 2018). This challenge affecting around 20% of cultivable land globally is degrading soil health, resulting in stunted and uneven plant growth (Machado and Serralheiro 2017). Soil salinization reduces agricultural output, loss of jobs, increasing food prices, enhanced hunger and degraded human health status. Declining agricultural output means lower income for farmers and a threat to their safety net.

Consequently, the price rise of animal feed and meat further threatens the food security. When institutions and policies are weak in handling food security, especially in developing countries, rising food prices lead to social unrest and violent conflict (Bellemare 2012; Smith 2014). Any desire to explore new and favorable frontiers for agriculture will increase natural vegetation removal and worsen the climate challenge.

The susceptibility to climate change-related risks and tragedies is most significant for least developed countries (Africa, Asia and Latin America) in the tropical and sub-tropical regions who rely mainly on agriculture-a climate-sensitive source of livelihood (CRED and UNISDR 2017). The rising temperature will worsen inequality across rich and poor nations. Furthermore, penury incidence is way higher in rural environments than the urban settlements of these least developed countries (FAO 2018; Gondwe 2019; Mba et al. 2018). The negative implications of climate change on agriculture and soils in these regions will exacerbate poor people's existing poverty status and make the non-poor vulnerable to poverty, with a mesh network of consequences that has negative implications on intra and intergenerational equity (UNDP 2019). Poor harvest from agricultural practices leads to insufficiency in farmers' income and inability to synchronize the income with the increasing price hikes of other commodities and needs. With the farmer's household having a larger household size, the dependent individuals face the challenge of meeting food needs, medical facilities, appropriate sanitation and primary education among others (Adepoju and Yusuf 2012). Poor nutrition degenerates to stunted growth, challenges intelligence, weakens a girl child's reproductive ability, reduces output, leads to poor health and reduces the overall life expectancy (Chinyoka 2014; FRAC 2017).

Furthermore, farmers' limited income threatens their access to medical care, thus posing a huge threat to men, women and children. Income stress also impedes children's educational progress, leading to a high rate of school drop-outs and lost potentials. With little income in educating and responding to children's health needs and a child's sex is preferred in individual communities, and this scenario worsens the gender inequality (Ajala 2017). Dropping out from schools and lack of guidance exposes the individuals to societal odds, reduces societal dignity, enhances vulnerability and makes them a threat to the progress, peace and security of the communities (OPHI and UNDP 2019; UNDP 2019). For example, a girl in a rural community who drops out of school without primary education lacks a basic understanding of herself and society. She could become vulnerable to early pregnancy, migrate to an urban area for prostitution, engage into child/early or forced marriage (CEFM) and in turn, impact her health, worsen her economic status and enhance societal ills (USAID 2015). For a male child, the need for resources to cater to his needs does arise as he grows older. This could lead to rural–urban migration which adds to the challenges of meeting the needs of urban residents, thereby exacerbating the urban climate challenge. In the face of high competition for resources, the resource stressed and educationally weak people engage in unhealthy societal practices to degrade peace and security (Mobjork and van Baalen 2016).

2.4 Climate Change, Education in the Tropics, Health and Risks to Sustainable Development

Rising temperature decreases human educational productivity, degrades human health and loss of lives. Irrespective of the household's socioeconomic status, climate change undermines children's academic gains in the tropics (Randell and Gray 2019). Higher temperatures cause an unfavorable learning environment, incomplete course content and poor examination results (Mbah 2014). In summer, residents continue to increase the utilization of fans and air conditioners to reduce their surroundings' temperature and gain a sense of comfort, which further exacerbates the pressure on unsustainable natural energy. This increasing demand for energy (unsustainable consumption) is increasing dissipation of heat into the surroundings, thus adding more CO_2 in the atmosphere and worsening the climate challenge. The condition is worse in urban areas where the temperature values in cities are a few degrees higher than the surrounding rural areas (Enete 2015; Ojeh et al. 2016). This temperature discrepancy results from a phenomenon termed urban heat island effect, and it has been associated with light absorption of surfaces, reducing vegetation with structures and waste heat. The condition affects air quality in urban environments, increases the temperature and stresses the native species.

The consequences of climate change-related heat on man include 'cerebral-spinal meningitis', skin cancer, cardiovascular impairments, old age respiratory disorders, rising blood pressure, heatstroke, hyperthermia, and heat cramps diabetes-related conditions, morbidity and premature death (Monday 2019; WHO 2018). Furthermore, infants, the elderly, children, pregnant women, athletes, outdoor and manual workers, and the poor are more vulnerable to climate change-related impacts. Poor health reduces an individual's output, increases deprivations, enhances poverty and undermines national economic development contributions. Nations in the tropics (developing countries) are worst hit by the climate challenge (CRED and UNISDR 2017). With the existing inequality between these countries and developed nations, climate change-related heat will worsen the challenge of reducing inequality across these nations.

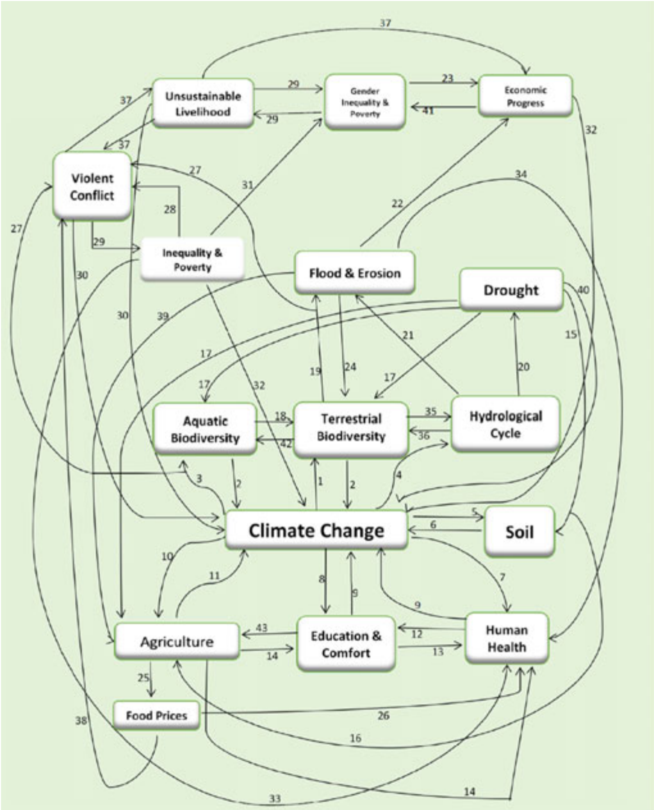
2.5 Climate-Well-Being Interconnected Risks—A Threat to Sustainable Development

Figure 1 summarized the interconnected risks associated with climate change outlined in the previous sections. The vicious cycle gives a guiding view to widen our understanding of how the unhealthy rise in global temperature is altering our planet's regenerative capacity and the prospects of achieving the sustainable development goals.

3 Adaptation and Mitigation to Climate Change—Defining a Safe Corridor for Humanity

Given the global community's climate challenge, a safe corridor needs to be mapped to deal with its root causes and to adapt to its associated impacts. It is well convincing that the consumption of fossil fuels and the subsequent emissions exacerbate the likelihood of its effects (UNDP 2008). Additionally, considering such adaptation blueprints become real if the target is to reinforce a rigorous sustainable development strategy and protect habitats. Mitigation and adaptation strategies cannot be addressed in isolation. They are not mutually exclusive but are dynamic, and have evolved (Davies et al. 2013a, b; Rasul and Sharma 2016). At the twentieth century's expiry, the objective was to reduce climate risks, impacts, and uncertainties and the scope was limited to specific locations and sectors. But at the beginning of the twenty-first century, the approaches were broadened to embrace trans-sector and trans-boundary; non-climate stressors; reducing climate risk with development-oriented agenda such as poverty reduction, strengthening the minority rights and protection of vulnerable groups.

Following the complex interaction of climate-impacts-management options and human well-being nexus approaches that detect less harmful tradeoffs and yield more productive synergies in human goals are scaled higher in proffering solutions to the climate challenge for securing a resilient planet (Liu et al. 2018). Akanwa et al. (2019) opined on the need for environmental greening and agroforestry in human settlements as an option for adaptation and mitigation to climate change. While this approach minimizes the challenges associated with the unhealthy rise in global temperature, it also strengthens food security and community resilience to climate shocks. According to ICLEI (2012), mitigation seeks ways to reduce greenhouse gas emissions through lowering energy consumption by strengthening local food production; improving the efficacy of water and energy delivery; enhancing renewable energy sources and reducing waste generation. Further, enhancing carbon sequestration by promoting healthy forest; promoting buildings that regulate weather conditions and deploying economic strategies can help mitigate the problem. These approaches should be applied in ways that simultaneously improve communities' buoyancy to the reality of changing climate (adaptation) and sustain environmental quality. For



1. Increase pests, invasive species and other stressors, decreasing forest productivity
2. Decrease in forest productivity and reducing capacity to absorb carbon dioxide.
3. Alteration of aquatic chemistry, e.g. through acidification, hypoxia
4. Melting of ice caps
5. Organic matter in the soil is decomposed, reducing soil nutrient
6. Decomposed organic matter in the soil is lost as CO_2 to the atmosphere
7. Weakens human health and premature death
8. Unfavorable learning condition and poor performance
9. Utilizing unsustainable energy for fans and air conditioning in order to gain a sense of comfort
10. Increase threat of C_3 weeds to food production
11. Exploring new frontiers for agriculture and removal of natural vegetation
12. Recurrent poor health weakens educational output
13. Dropping out from school, early pregnancy, prostitution; child, early and forced marriage (CEFM)
14. A poor harvest and consequently poor income undermine parents and caregivers' ability to train children and meet other basic needs
15. Increase dependence on groundwater, especially in coastal areas leads to soil salinization
16. Stunted and uneven plant growth
17. Reduce the potential of groundwater recharge
18. Threaten the survival of migratory species, e.g. migratory birds
19. Dwindling vegetation
20. Decrease precipitation
21. Increase the frequency of precipitation
22. Tangible and intangible losses
23. Lack of resources to cope with disaster due to patriarchy and gender bias
24. Relocation to safer and unexploited zones
25. Increase in food prices
26. Hunger and malnutrition
27. Resource pressure due to dwindling resources
28. Violent conflict worsens existing inequality and poverty
29. Raping, drug abuse, school drop-out
30. Reduces partnership and capacity to work together
31. More women and girls affected than men and boys
32. Increase dependence on natural resources for survival
33. Poor income weakens the ability to meet health needs
34. Poor sanitation and pollution of freshwater
35. Dwindling vegetation affects local climate
36. Local climate and precipitation affect the survival of indigenous flora and fauna
37. Dealing on drugs and arms impedes social security
38. Lack of strong institutions to manage price hikes and peaceful protests
39. Washing away of fertile soil, crop destruction and productivity
40. Warmer air holds more water vapour (a greenhouse gas)
41. The negation of women's value impedes contributions to the development
42. Decrease terrestrial vegetation increases flooding and siltation
43. Poor educational achievement leads to lost potentials and undermines innovations

Fig. 1 A vicious cycle of 'climate-well-being' interconnected risks example, reducing vehicle travel mileage through price hikes of fuel (mitigation) should be accompanied by adaptation strategies that residents can accommodate price hikes, such as making goods and services available to them. This assists in stabilizing or strengthening their disaster coping capacity and reducing vulnerability to climate risks and poverty.

As there are no specific adaptation strategies (Rasul and Sharma 2016), it is essential to define the interconnected risks facing communities and develop designs that accommodate local priorities while integrating global needs. In communities and cities with recurrent climate change associated floods, it is crucial to understand the natural vegetation that preceded human settlements because of deploying biomimetic designs that can coexist with floods, save water, reduce energy consumption and land use abuse. For example, India is characterized by monsoon flooding and in proposed city development, city developers design rooftops to mimic the banyan fig leaf's drip-tip system that allows water to runoff while simultaneously cleaning its surface (Gendall 2009). While occupants in such settlements could collect water in the wet seasons with a lightweight design that mimics the survival of the cactus plant in a desert environment (Nessim 2016), the excess water could be removed by mimicking local harvester ants that use multi-path channels to remove water from their nets (Gendall 2009). The varying survival circumstances of natural systems' evolution reveal that bio-inspired designs offer sustainable adaptation and mitigation strategies to the rising temperature (Sudhakaran 2017). These designs are efficient in resource use and ecosystem sustenance. They utilize just the energy and water they need, develop mechanisms to thrive in limited resources and recycle its waste.

Again, in seeking the most feasible crop type to cultivate in the face of limited access to water (drought) associated to climate change, in-depth analysis for several possible crops will reveal crops with minimum water demand, least ecological footprints and the market value of these crops (Daccache et al. 2014). While the desired characteristics are not usually associated with a single crop and the market value for these crops varies in space, appropriate mathematical models, time and investment will help define the crop with the highest net benefit and reduce vulnerability to the climate challenge. Liu et al. (2018) posit that biofuel processing requires 500 times more water compared to oil and gas. By this submission, adaptation strategies that seek to improve biofuel use should consider the high-water demand in biofuel development and how this water demand is related to regional characteristics, energy sustenance, food security, and ecological services and human well-being.

It is therefore important to understand where each adaptation and mitigation strategy fits into the interconnected climate change risks to identify synergies and tradeoffs in the pursuit of human objectives. The issues to consider in defining a sustainable adaptation strategy are usually complicated. They require huge investment and time if planners intend to address a broader scope of interconnected risks and reduce human suffering. According to United Nations (2019) and World Bank (2004), every single dollar spent on pre-disaster risk management (majorly for adaptation) in developing countries, losings of about six dollars can be averted. The nexus approach in defining adaptation strategies to climate change is more sustainable than a sectoral approach. They provide promising tools in charting a safe corridor for humanity and the diversity of life forms on the planet.

4 Conclusions

The condition of the global temperature is vital for the sustenance of life and the achievement of human goals. Unfortunately, the pursuit of these goals is altering the global climate and disrupting the smooth functioning of life processes. These disruptions degenerate to interconnected risks that add to existing human suffering, hamper their survival and exacerbate the climate challenge. The risks associated with our planet's rising temperature vary in space and time and cannot be addressed in isolation. It is pertinent to understand how the climate keeps changing, to explore the most feasible and productive opportunities to reduce the interconnected risks while considering local priorities and integrate global needs.

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Climate Change and Its Impacts on Businesses

Vicente Manzione Filho

Abstract Climate change is still an incipient issue, mainly in the scope of investment and corporate decision-making. Risks and opportunities of climate change exist and need to be assessed and incorporated into investment analysis in various economic sectors. Climate change is a global risk, with potential to impact industries and markets. It depends on the geographic location, business model, company preparation, technology availability, etc. Following this, several national and local laws and regulations were instituted in several countries aiming to establish parameters for reducing greenhouse gas (GHG) emissions and adaptation to the effects of climate change. This requires considerable investments in innovation and new technologies. In this backdrop, the current chapter delves deep into the understanding of the impact of climate change on business and other related aspects. Likewise, it evaluates how technological innovations can mitigate risks or generate opportunities.

Keywords Climate change · Business · Risk · Sustainable economies · Financial stability · Financial disclosure

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1 Context

Considered by several studies as a global megatrend, climate change gained great emphasis in the international sphere and businesses in 2005 with the entry into force of the Kyoto Protocol and the carbon market. In 2007, with the publication of the 4th IPCC report on climate change science, the documentary ‘An Inconvenient Truth’ and the ‘Stern Report’ on the Economics of Climate Change, the topic gained attention from the general public policymakers.

Following this movement, national and local laws and regulations were instituted in several countries aiming to establish parameters for reducing greenhouse gas (GHG) emissions and adaptation to the effects of climate change. This requires considerable investments in innovation and new technologies.

The Paris Agreement, signed in 2015, governs the GHG emission reduction measures that the signatory countries must pursue from 2020, through the implementation of the Nationally Determined Contributions (NDC). In Brazil, the elaboration of a National Strategy for the Implementation and Financing of NDC is currently being discussed. Through the PMR Project, the Economic Policy Secretariat of the Ministry of Economic assesses the costs and benefits of economic instruments for carbon pricing in the country.

In the scope of businesses, significant initiatives have taken place in the last five years. Especially noteworthy are those whose objectives include the inclusion of the business strategy theme whenever considered material from an economic and financial perspective.

Examples of these initiatives are the Task Force on Climate-Related Financial Disclosures (TCFD) and the Technical Bulletin on Climate Risks of the Sustainable Accounting Standard Board (SASB), which added to the robust CDP climate database and to signatory investors to the Principles of Responsible Investment (PRI), among others.

Despite this recent history, climate change is still an incipient issue, mainly in the scope of investment and corporate decision-making. Risks and opportunities of climate change exist and need to be assessed and incorporated into investment analysis in various economic sectors. Likewise, evaluating how technological innovations can mitigate risks or generate opportunities can mean individual businesses’ perpetuity.

As stated by Bloomberg and Pope (2017) in their book ‘Climate of Hope: how cities, businesses and citizens can save the planet,’ climate change should now be approached more pragmatically and assertively.

> Instead of debating long-term consequences, let’s talk about immediate threats. Instead of arguing about making sacrifices, let’s talk about how we can make money. Instead of the environment versus the economy, let’s consider market principles and economic growth. Instead of focusing on polar bears, let’s focus on children with asthma. Instead of putting all

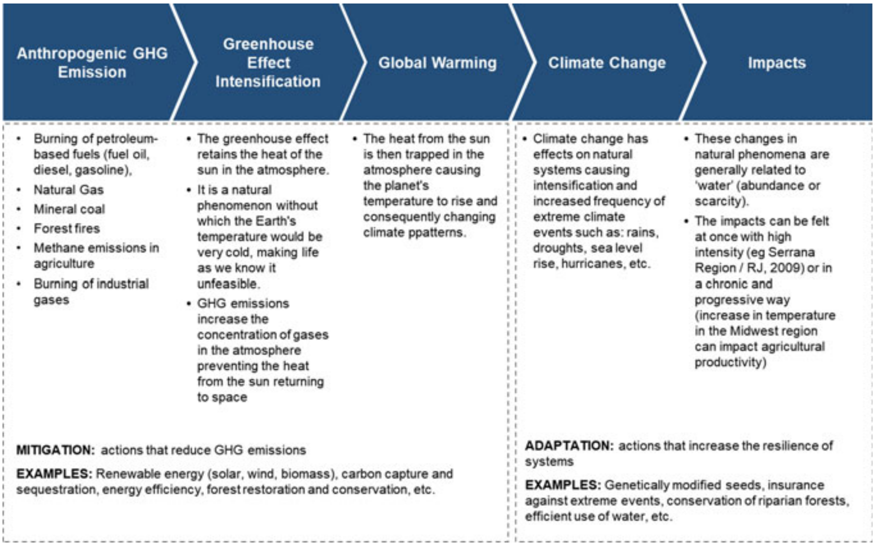

Fig. 1 Climate change causal link. *Source* author

> hope in the federal government, we are going to empower businesses, cities and citizens to accelerate the progress they already make on their own.[1]

2 Climate Change

In basic terms, the climate change process begins with people's actions and ends impacting them. This is because the activities we carry out emit GHG. As the Planet cannot absorb all anthropogenic emission, GHG concentrations have been increasing year by year. Thus, thermal energy from the sun is trapped in the atmosphere, causing heating. In turn, global warming causes changes in the climate and the environment, which ultimately affects our livelihoods. Figure 1 illustrates this causal link.

According to Stern (2010), during the period 1995 to 2005, the rate of increase in the annual carbon dioxide concentration, of 1.9 ppm, was higher than ever. The annual emissions of carbon dioxide increased from 23.5 Gt CO_2 per year in the 1990s to 26.4 Gt CO_2 per year from 2000 to 2005. This increase in CO_2 concentration is considered responsible for the rise of 0.8 °C in the Planet's temperature compared to the pre-industrial period.

The IPCC warns that an increase of more than 2 °C in the Planet's average temperature can cause radical changes in the climate as we know it today. By maintaining the status quo, forecasts estimate an increase in annual GHG stocks of around 3–4 ppm, which would raise the concentration levels from the current around 400 ppm

[1] Bloomberg and Pope (2017) 'Climate of Hope: how cities, businesses and citizens can save the planet'.

Table 1 Probability (%) of temperature increase in relation to GHG concentration levels. (in ppm CO_2)

Stabilization level (in ppm CO_2)	2°C	3°C	4°C	5°C	6°C	7°C
450	78	18	3	1	0	0
500	**96**	44	11	3	1	0
550	**99**	69	24	7	2	1
650	100	94	58	24	9	4
750	100	99	82	47	22	9

Source Stern (2010)

to 580–630 ppm by the middle of this century and between 800 and 900 ppm until the end of the century. For example, concentrations of CO_2 in the atmosphere at levels of 500–550 ppm would result in a 96–99% probability of an increase in temperature by 2 °C. The table below illustrates these probabilities (Table 1).[2]

In this sense, the increase in temperature would imply more intense and frequent extreme weather events, with significant risks of high magnitude and impacts on people, physical assets and even the location of production in several industries. Thus, reducing GHG emissions is critical.

3 Climate Change Risks, Opportunities, and Impacts

Climate change is a global risk, with potential to impact industries and markets. According to the latest report by the World Economic Forum,[3] '2020 Global Risk Outlook', aspects related to climate events are of high probability and high impact. Extreme weather events, natural disasters, failure to mitigate/adapt to climate change and water crises are among the top global risks identified, are some examples of hazards.

According to SASB,[4] climate risks can manifest as follows:

- **Specific risk** -> affects only a particular industry or company. It depends on the geographic location, business model, company preparation, technology availability, etc. It is necessary to understand the magnitude, probability and timing of each industry's risks.
- **Systematic risk** -> is the uncertainty inherent in the entire market and, therefore, not diversifiable. For example, climate risks will continue to affect the global

[2] Stern (2010).

[3] https://www.weforum.org/reports/the-global-risks-report-2020.

[4] SASB—Sustainable Accounting Standard Board (2016). Climate Risk. Technical Bulletin #TB001-10,182,016.

price of energy, agricultural productivity, migration, etc. The impact varies from industry to industry, but almost none is immune.

- **Systemic risk** -> can lead to the collapse of an entire market or the financial system as a whole.

Investors and the Board of Directors need to understand these different types of risks. They influence the ability to diversify risks, conduct appropriate investment financial analysis and manage the risks. But where can investors and company's management get reliable information about climate change?

3.1 Main Sources of Information: The Materiality of Climate Change

There are three primary global sources of public information regarding climate change and its potential impacts on businesses:

- **Task Force on Climate-related Financial Disclosure (TCFD)**: In December 2015, the Financial Stability Board (FSB) established this initiative to develop a standard for disclosing information on climate change that can promote more informed investments and, in turn, enable stakeholders to understand their exposures to carbon concentrations and climate-related risks.
- **Sustainable Accounting Standard Board (SASB)**: it is the Independent organisation based in the USA dedicated to setting standards to improve the capital market's efficiency, promoting the disclosure of material sustainability information that meets investors' needs. The mission will help public companies to disclose relevant information to investors in SEC documents, such as Forms 10-K, 20-F and 40-F, in a cost-effective and useful manner for the decision. SASB maintains standards for 79 industries, focusing on sustainability factors that are reasonably likely to have material financial impacts.
- **CDP—Driving Sustainable Economies**: CDP is a non-profit institution, based in London, which manages the global disclosure system for investors, companies, cities, states and regions to manage its environmental impacts. Over the past 15 years, it has created a system that has resulted in a consistent engagement of companies and cities on environmental issues worldwide.

The information in these organisations' publications and databases is a valuable introduction resource for understanding the connections between climate change and companies in several sectors.

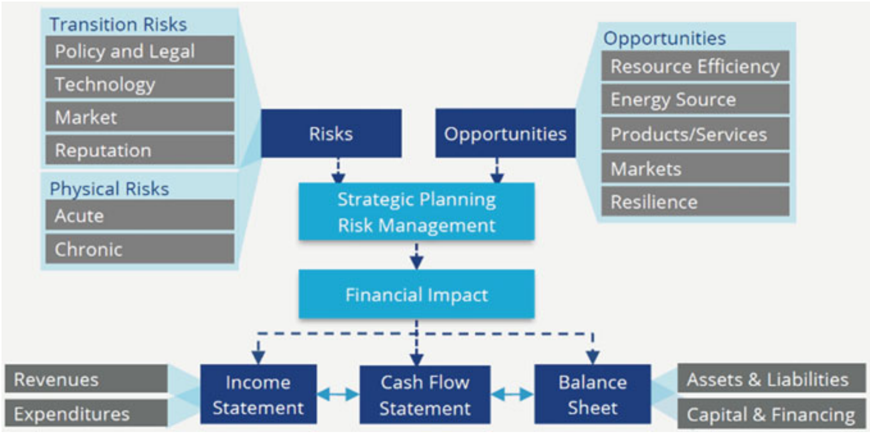

Fig. 2 TCFD Framework. *Source* TCFD (2017)

3.2 *Defining What is Material*

For SASB (2013),[5] "each company is ultimately responsible for determining which information is relevant and which data should be included in the mandatory and periodic form sent to the SEC—Security and Exchange Commission. In identifying sustainability topics that are likely to be material for companies in a specific industry, SASB follows the definition of materiality adopted by US law and jurisprudence. According to the US Supreme Court, the information is material if there is 'a substantial probability that the reasonable investor would have seen the disclosure of the omitted fact as having significantly altered the 'total mix' of the information made available".

Consequently, it identifies that the relevant environmental and social issues are likely to impact a company's financial condition or operating performance and, therefore, are more critical to investors.

Bringing this concept to the climate change domains means identifying which kind of risk/opportunities companies are exposed to. In that sense, there has been significant evolution over the last few years, especially regarding the harmonisation of concepts. For instance, through its guide[6] 'Implementing the Recommendations of the Task Force on Climate-related Financial Disclosures' TCFD has set the categories of risks and opportunities and its potential impact on value (Fig. 2).

Although climate risks exist and have gained repercussions within organisations, an understanding of the relationship between climate change and its potential financial impact is still incipient. Thus, it is paramount for companies to understand, assess and prioritise which climate change risk is material for them to address strategically.

[5] SASB (2013).

[6] TCFD (2017).

3.3 *Impact of Climate Change on the Processed Food Sector Value Chain*

Understanding how each sector is exposed to climate change risks and opportunities is the first step towards setting a climate change strategy. In this sense, it is presented below a case study of applying a methodology to prioritise climate change material risk in a Brazilian processed food company. The analysis considers the following value chain parts: agriculture, ports, fabric and distribution.

Agriculture[7]

Climate change has created challenges for the agriculture sector—and will continue to do so. It induces increases in temperature, rainfall variation, and extreme weather events' frequency and intensity, hence increasing pressures on global agricultural and food systems. The crops we grow for food, fibre and energy need specific conditions to thrive, including the ideal temperature and sufficient water. To some extent, warmer temperatures can benefit certain crops' growth in some parts of the world.

However, if temperatures exceed the ideal level of a crop or sufficient water and nutrients are not available, yields tend to fall. An increase in the frequency of extreme events, especially floods and droughts, also harms crops and reduces yield. Climate change will change the conditions for agriculture. This can lead to differences in comparative advantage between regions and consequently to changes in agricultural trade.

Evidence from OECD studies indicates that wheat-producing regions such as Canada, the USA and Argentina can benefit from rising temperatures. On the other hand, concerning palm oil, areas of Malaysia and Indonesia are already severely impacted by the effects of extreme weather events. In contrast, soy production in mid-west Brazil may be adversely affected by increased temperature.

Besides, in general, agriculture is also a significant emitter of greenhouse gases, especially N_2O, although there are no regulatory moves to mitigate GHG emissions. On the contrary, we see voluntary initiatives such as the Federal Government's ABC—Low Carbon Agriculture Programme and the WBCSD Climate Smart Agriculture initiative.

Ports[8]

Climate change can aggravate or trigger coastal erosion and flooding phenomena through environmental forces such as waves, winds, currents and tides, affecting the safety of the population and economic activities in coastal areas. Some points in Brazil are considered to have a high degree of flooding near Fortaleza, João Pessoa, Recife and Aracajú due to the high population density. Hangovers on the coast of

[7] OECD (2019).

FAO (2016).

[8] SMC Brasil Project. A Proposed approach for the establishment of probabilistic regime of Brazilian coastal flooding area thematic document. Brasilia, DF MMA 2018.

Ceará can cause coastal flooding. The hangovers that reach this region are associated with extratropical hurricanes in the northern hemisphere, causing storms that result in the arrival of waves on the northeast coast of Brazil.

The combination of higher average altitudes and low population density gives the Bahian coast a low risk to the natural coastal flooding process. However, in places associated with river outlets with a high population density, such as in the cities of Salvador, this risk becomes elevated. In the Guanabara Bay area, all drainage networks from the Serra do Mar converge. This factor, together with the high population density, in situations of tides associated with the passage of frontal systems and accompanied by high precipitation, makes the area exposed to flooding.

From the southern portion of Baixada Santista to Itajaí region, the degree of risk to flooding reached medium to high values, due to the combination of three crucial ports, relatively high population densities and the socio-economic importance of these centres.

Fabric[9]

High energy dependence on operating large industrial units for use in stages such as heating/cooking, cooling, packaging and transporting. Energy production and consumption contribute to climate change due to GHG emissions and can potentially impact the results of the operations of processed food companies indirectly but materially. Most of the sector's direct Scope 1 emissions refer to natural gas burning to generate heat and electricity with a low impact level.

Industry spending on fuel and electricity represents about 1.07 and 1.80% of the total cost, respectively (2.87% of energy expenditure). Due to relatively high energy dependence, companies recognise the risk of rising prices and restricted supply as material concerns in their 10-K Forms—a significant opportunity for companies to implement projects to improve energy efficiency and generate cost savings.

Water management is an increasingly material issue for companies in the sector, as large quantities of water are needed in the production process. As the global population is expected to grow to 9.2 billion by 2050, water demand will increase. Simultaneously, increased pollution and climate change will create significant operational risks for processed food companies, especially those operating in water scarcity regions. Companies in the sector have started to implement programmes to reduce water consumption in direct operations.

In addition to the cost-efficiency of limiting water consumption, companies recognise the need to understand water scarcity risks in all their operations. Companies operating in regions with water scarcity can implement water efficiency initiatives to reduce the risks of scarcity and increases in water prices in these regions.

Distribution[10]

The road transport sector faces risks and opportunities related to its environmental impacts, mainly due to the expansion of climate regulations. The regulatory costs

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[9] SASB. Industry Brief Processed Food. June 2015.

[10] SASB. Industry Brief Road Transportation. September 2014.

associated with GHG emissions and air pollutants are threatening the industry's profit margins. However, optimising fuel management through technological innovation offers an opportunity to reduce operating costs.

Also, the positive public perception resulting from GHG emissions' effective management can improve the brand's reputation and value. In their 10-K Form, truck companies recognise the risk to revenue for environmentally conscious customers, diverting business to more fuel-efficient competitors. Failure to comply with customers 'sustainability requirements could have a significant adverse effect on the results of companies' operations and could lead to a substantial deterioration in market share.

As the externalities of climate change continue to worsen and road transport increasingly becomes the focus of regulations to limit emissions, the likelihood and magnitude of these impacts will likely increase in the short and medium-term. The extent of these impacts can be estimated using companies' Scope 1 emissions, in absolute terms and relative to their peers, considering the mitigation efforts reflected in concrete emissions reduction targets. It can also be assessed through the carriers' fleets' energy efficiency and energy mix (renewable energies).

Using the information above and the TCFD and SASB information, Table 2 summarises the evidence of the impacts of climate change risks on the processed

Table 2 Summary of evidence on the impacts of climate change on the food sector value chain

		IMPACT ON VALUE CHAIN				POTENCIAL FINANCIAL IMPACTS				
CATEGORIES		AGRICULTURE	PORTS	FABRIC	DISTRIBUTION	INCOME	EXPENDITURES:OPEX	ASSET:CAPEX	LIABBILITIES	FINANCIG DEBT/EQUIT
RISKS	**PHYSICAL RISKS**									
	Acute (Punctual, unpredictable)									
	More intense droughts									
	More intense rainfall / floods									
	Higher wind speed									
	Chronic (progressive, predictable)									
	Changes in precipitation patterns									
	Extreme variability in weather patterns									
	Increased average temperatures									
	Rising sea level									
	TRANSITION RISKS									
	Public Policies, Legal									
	Greater obligations for reporting emissions									
	Regulation on emissions, licenses									
	Carbon tax									
	Fuel / energy taxes and regulations									
	Marketplace									
	Rising raw material costs									
	Change geographic location of supply									
OPPORTUNITIES	**Resource efficiency**									
	Use of more efficient modes of transport									
	Reduction in the use and consumption of water and energy									
	Energy sources									
	Use of lower emission energy sources									
	Use of public policy incentives									
	Decentralised power generation									
	Resilience									
	Renewable energy and energy efficiency programs									

Source author, adapted from TCFD, SASB and CDP food sector value chain and their potential financial impacts. Most risks if materialised would affect expenditures with agriculture and fabric being more impacted. The most critical risk category is more intense rainfall/floods that would jeopardise all value chain.

Figure 3 depth the analysis considering the evidence of material impacts of climate change on a Brazilian food company. If materialised, chronic and acute physical risks would result in inability to produce and supply interruption, an increase in operating costs/expenses, more capital expenditures, and damage to property, machinery, and equipment.

As companies increase their understanding of how climate change affects operations and finance and considering the scarcity of financial and human resources, there is an increasing need to prioritise which risks are material for business.

4 Prioritising Climate Climate Change and Opportunities

With the understanding of the sector climate change potential implications, what companies need to assess are the risks or opportunities that most threaten their ability to value generation/protection.

4.1 Methodology

The methodology[11] described below allows companies to prioritise climate change risks and opportunities according to the company's materiality. The process has been applied to some companies in the Brazilian market. Figure 4 exemplifies the six steps to the methodology application.

The 6 Steps methodology

1. Identification of which categories of risks and opportunities suggested by the TCFD applies to the processed food sector: Physical Risks (Acute, punctual and unpredictable/Chronic, progressive and predictable); Transition Risks (Public Policies, Legal/Market); Opportunities (Resource Efficiency/Energy Sources/Resilience).
2. The links in the value chain considered were (A) Agriculture; (P) Ports); (I) Industry (Fabric); (D) Distribution. The TCFD report 'Implementing the recommendations of the TCFD, June 2017' and 'SASB Industry Briefs'

[11] Gestão Origami's proprietary methodology. I am thankful to Bruno Vio my partner at Gestao Origami and Fabio Crotti an independent financial consultant and friend. There were insightfull conversations and great technical imputs to the development of the methodology.

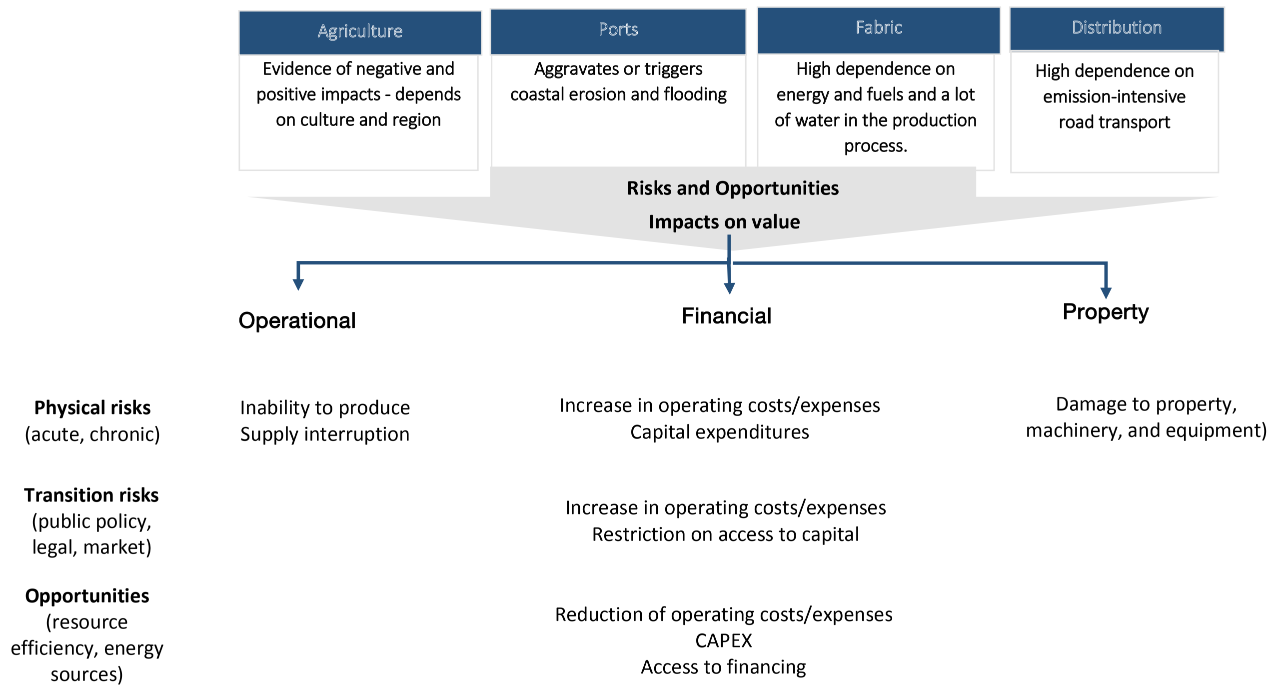
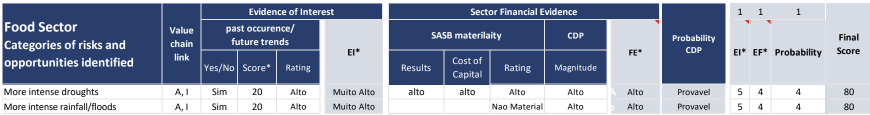


Fig. 3 Summary of evidence on the material impacts of climate change on a Brazilian food company value chain. *Source* author, adapted from TCFD, SASB and CDP



Food Sector Categories of risks and opportunities identified	Value chain link	Evidence of Interest				Sector Financial Evidence					Probability CDP	1	1	1	Final Score
		past occurence/ future trends			EI*	SASB materilaity			CDP	FE*					
		Yes/No	Score*	Rating		Results	Cost of Capital	Rating	Magnitude			EI*	EF*	Probability	
More intense droughts	A, I	Sim	20	Alto	Muito Alto	alto	alto	Alto	Alto	Alto	Provavel	5	4	4	80
More intense rainfall/floods	A, I	Sim	20	Alto	Muito Alto			Nao Material	Alto	Alto	Provavel	5	4	4	80

Fig. 4 Example of the methodology application. *Source* author

‘Processed Food’, ‘Agricultural Products’ and ‘Land Transport’ were considered as primary references. The focus of the analysis was on issues related to GHG emissions, energy and water.

3. To define whether the category of R|O[12] is applicable, to characterised the profile of the value chain looking for evidence-based on secondary research about the occurrence or strong trends of R|O to materialise. The objective was to filter and direct the search for **Evidence of Interest (EI)**:
4. .Occurrences in the sector, in the business and/or in the locations where units are installed over the last 5 years (Yes/No)
5. .The materiality of the category of R|O as presented in the ‘SASB Industry Briefs’ (High/Medium/Low/Null) + Ruler below
6. No, 1 -> R | O is generic for companies in the food sector; there is no past evidence of material impacts directly on the company;
7. Yes, 2–5 -> R|O has already impacted/may impact the company indirectly through the value chain (agriculture, ports, distribution); the financial/operational impact tends to be low-medium;
8. Yes, 6–9 -> R|O has already impacted/may impact the company indirectly through the value chain (agriculture, ports, distribution); the financial/operational impact tends to be medium–high;
9. Yes, 10–13 -> R | O has already impacted/may impact the company directly; the financial/operational impact tends to be low-medium;
10. Yes, 14–17 -> R | O has already impacted/may impact the company directly; the financial/operational impact tends to be medium–high;
11. Yes, 18–20 -> R | O has already impacted/may impact the company directly and indirectly; the financial/operational impact tends to be high.
12. The combination of the possibilities between ‘i’ and ‘ii’ (Very High, High, Medium, Low, Very Low) allowed EI to be defined and selected from the R|O applicable to each invested sector/company.
13. In addition to the EI, an attempt was made to identify, the **Financial Evidence (FI)**:

    i. Occurrence: Through the ‘SASB Industry Brief’, FI was identified in the Results, Balance Sheet and Capital Cost, being classified as High, Medium, Low or Nil;
    ii. Magnitude: Based on the responses of 540 companies in the food sector to the CDP Programmes Climate Change Supply Chain Global (2016) and Climate Change Latin America (2017), answers to questions about risks

[12] R: Risk | O: Opportunity.

and opportunities were analysed. The focus was to assess the potential financial impact (Very High, High, Medium, Low, Very Low, Unknown, Nil). This is an essential source of practical information for defining the materiality of the R|O.

iii. The combination of the possibilities between 'i' and 'ii' (Very High, High, Medium, Low, Very Low) allowed to define the EFI of the R|O.

14. The **probability** was also extracted from the CDP database as per item 4 above and classified as follows: Very Likely, Probable, Neutral, Unlikely, Very Unlikely, Unknown and Nil.
15. For the final score, the scores were weighted: EI x EF x Probability. In this step, weight equal to 1 was considered for the three variables. A maximum score equal to 100.

4.2 Climate Change Impacts on Businesses: Material Risks and Opportunities

Table 3 shows the outcome of the methodology application. The main risks related to physical aspects of climate change are high in magnitude and likely to materialise and are connected to agriculture and industry. The main transition risk is increasing raw material costs (water and energy) while the foremost opportunity is renewable energy and energy efficiency programmes.

It is worthy to note that none risk/opportunity reached the maximum score allowed by methodology: 100. It means that climate change risks have fewer impacts on the food sector than in other sectors of the economy.

For instance, the methodology has also been applied to other sectors, and the results are shown in Table 4. As can be seen, industries with high GHG emission intensity are more likely to suffer climate change transition risks.

5 Conclusion

With this kind of information, companies have a rational to build their climate change knowledge and focus on managing the most critical risk. Key information to be used in such analysis include but are not limited to:

- Legislation and climate litigation around the world;
- Emissions trading and taxation regimes, including carbon prices;
- Sources of financing for mitigation and adaptation;
- Regulatory renewable energy incentive regimes in various countries;
- Energy and fuel prices;
- Databases on natural disasters;
- Water stress regions;

Table 3 Summary of evidence on the impacts of climate change on the food sector value chain

Risk/Opportunity		Value chain	Magnitude	Probability	Score
Risk	More intense droughts	A, I	High	Likely	80
Risk	More intense rainfall/floods	A, I	High	Likely	80
Risk	Rising raw material costs (water and energy)	A, I, D	Medium	Likely	60
Opportunity	Renewable energy and energy efficiency programs	I, D	Medium	Likely	60
Risk	Changes in precipitation/temperature patterns	A	High	Likely	48
Risk	Increased average temperatures	A	High	Likely	48
Risk	Greater obligations for reporting emissions	I	Low	Very Likely	40
Risk	Higher wind speed	I	Low	Likely	32
Risk	Rising sea level	P	Low	Likely	24
Opportunity	Reduction in the use and consumption of water and energy	I	Unknown	Unknown	16
Opportunity	Use of more efficient modes of transport	D	Unknown	Unknown	12
Opportunity	Use of more efficient modes of production and distribution	I, D	Unknown	Unknown	12
Risk	Carbon tax/emissions trading schemes	I	Low	Likely	8
Risk	Change geographic location - supplies	A	Unknown	Unlikely	8
Risk	Emissions regulation, reduction targets	I	Very low	Likely	4
Opportunity	Use of lower-emission energy sources	I, D	Unknown	Unknown	3
Opportunity	Decentralised power generation	I	Unknown	Unknown	3
Opportunity	Use of public policy incentives	I	Unknown	Unknown	1

Source author

Table 4 Risks and opportunities in some sectors other than food

Risk/Opportunity		Sector	Magnitude	Probability	Score
Risk	Emissions Trading Schemes	Cement	High	Very Likely	100
Risk	Emissions Trading Schemes	Mining & Metals	Very high	Very Likely	100
Risk	Rising raw material costs (energy)	Mining & Metals	Very high	Very Likely	100
Risk	Emissions Trading Schemes	Steel	Very high	Very Likely	100
Risk	Rising raw material costs (energy)	Steel	High	Very Likely	100
Risk	Rising raw material costs (water)	Pulp & Paper	High	Very Likely	100
Opportunity	Use of lower-emission energy sources	All	High	Very Likely	100

Source author

- Charges for water use and prices of water withdrawal.

Data of this nature are variables that can affect the feasibility analysis of a project and, therefore, should be considered in any investment decision-making process.

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Climate Change Hastening Heatwaves: A Pakistan Scenario

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Abstract Heatwaves originate when air is trapped in a specific area for a longer time, causing an increase in temperature, having harmful impacts on the environment and human health. The main reason for this phenomenan involves high-pressure air circulation systems that prevent the near ground air to rise. It traps warm ground air in place and results in no rain. In modern times, heatwave events are arising three times more often than they did earlier in the 1960s. Scientists claim that 80% of heatwaves are due to anthropogenic activities. In addition to the heated air, elevated humidity also causes a rise in heat wave incidents. This intensely heated air is the deadliest form of extreme weather events, causing more deaths than any other climate disaster. These heatwaves cause health illness and even deaths of young children, the elderly, livestock, and wild animals. This chapter analyzes the sources and effects of climate-driven heatwaves with special emphasis on Pakistan's situation. Also, we have elucidated the heatwave impacts on human health. A correlation is also established to identify the possible interaction between urbanization and the increasing intensity of heatwaves.

Keywords Climate change · Heatwaves · Environmental Impacts · Extreme weather events · Human health

1 Introduction

The urbanization trend has now continued for decades (UNFPA 2007), with above 50% of the population (around 3.5 billion people worldwide) living in urban areas (o'Brien et al. 2004). The effects of urbanization include natural disasters and the vulnerability of social ecosystems which are consequently changing enormously. At local or regional level, the natural resource depletion and ecosystem destruction that occur due to urbanization caused changes in the surrounding terrestrial and aquatic ecosystems (Alberti 2005). Anthropogenic factors like the destruction of

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forests and, occupation of alluvial land cause the ecosystem losses, for example, the destruction of urban soil results in decreased water permeability, thereby increasing flood potentials.

Climate change impacts are growing day by day, demanding serious consideration and promotion of these activities necessary to understand its adaptation strategies (Perkins et al. 2018).

2 Ecosystem Services to Urban Areas

A relatively small and narrow geographic area comprising buildings, a set of modern infrastructure, and other structures is termed an urban area (Kreimer et al. 2003). Different countries define urban areas differently, but the current studies define a city as a permanent settlement. However, it is not (Yearbook 2007) easy to define urban areas concerning multidisciplinary perspective (Pelling 2003).

A city is understood as one complete ecosystem made up of various small artificial ecosystems (including lawns, parks, street trees, ponds, forests, lakes, streams, farmlands, wetlands) and natural ecosystems (Bolund 1999) rendering the essential services like carbon sequestration, climate regulation, water regulation, and air purification (Kallis 2008). Runoff reduction, lowering the temperature, mitigating floods and heatwaves, increasing ventilation, and enhancing water storage are the benefits of these urban green spaces (Ward et al. 2016). As for millennium ecosystem assessment (Fitter et al. 2010), they provide the following most important services (Ecosystems 2005):

i. Cultural and entertainment services,
ii. Soil degradation regulation,
iii. Support services for nutrients cycling and soil formation,
iv. Regulatory services for droughts and floods,
v. Water regulation, and
vi. Food provisions.

3 Climate Changes Scenario in Pakistan: Relations with the Global Context

Currently, the whole world is facing the effects of climate change while case scenario of developing countries is relatively more severe (Rahman and Lateh 2017; Shahvari et al. 2019). The insufficient institutional capacity, abuse and lack of resources, lack of knowledge and awareness for policy-making and their low economy are the main reasons for these severe impacts (Wahid et al. 2019). The world has already observed the *El-Nino* and *La-Nina* phenomenas in its ecosystems and hydrological reserves. From 1895 to 1995, the temperature rose by 0.4 °C (Meehl and Tebaldi 2004; Rauf et al. 2017).

Due to the depletion of hydrological resources, it is expected that Pakistan will also be exposed to climate change and its effects (Chaudhry et al. 2009) in a more severe way. The temperature in Pakistan will rise from 0.9 °C in 2020 to 1.5 °C in 2050. During 1998–2004, Pakistan faced the worst drought in history (Hussain and Mumtaz 2014). Around 84% population and 76% deaths in Baluchistan province occurred due to heatwaves (Ullah et al. 2018), and it is predicted that this condition of high temperatures, droughts, pests, diseases, health problems, and lifestyles will persist for many years to come (Hussain et al. 2018). Climate change will have harmful effects worldwide in terms of frequent famines, rising temperature, changed precipitation patterns (Sohoulande Djebou and Singh 2016), and agricultural destruction (Rosenzweig et al. 2014). Pakistan too will be facing the devastating impacts of climate change exacerbated by its low per capita income and, inadequate capacity building facilities (Bhatti et al. 2018).

Pakistan's economy is agriculture-based, but it still does not have sufficient infrastructure to adapt and mitigate the effects of climate change (Khan et al. 2016). It is among the top vulnerable countries facing severe impacts of climate change due to its water resource dependency for agriculture (Bhatti et al. 2018; Malik et al. 2012).

Furthermore, all regions are not equally affected by climate change (Malik et al. 2012). It is incredibly worrying as climate change will have more severe effects on poor farmers (Ali and Erenstein 2017). The 2010–2011 floods showed that farmers in rural areas are more vulnerable to climate-driven natural disasters (Gorst et al. 2018). Therefore, climate change significantly impacts the economy and livelihood in rural areas (Mukwada and Manatsa 2018).

Although Pakistan's contribution to global GHG emissions is insignificant, it is among the countries facing its adverse impacts (Baloch and Suad 2018). In 2012–2014 alone, more than 1 million people were affected by floods, which threw them into chaos. Since 2015, the number fell below a million, as efforts were made continuously by individuals, nonprofit organizations, and other environmentalists to curb and adapt to climate change (Salamanca et al. 2017).

4 Heatwaves

The term heatwave refers to various weather conditions from moderate to severe. In the event of a disaster or emergency, heatwaves can affect certain aspects of overwhelming public services. Heatwaves are a natural hazard that occur due to climate change driven events. Extreme temperature events can have significant health effects by posing challenges to public health and civil protection services. Besides, one greatest effect of human-made climate change in the future will be an increase in heat waves that will become more intense with time (Change 2007). As the heatwaves topic has become a rapidly growing field of epidemiological research, most countries/ regions of western Europe have taken some public health measures against them. While we know more about who is most prone to heatwaves, there is little evidence of preventing heat-related deaths most effectively.

4.1 Heatwaves and the Human Body

Healthy adults have an effective calorie regulation mechanism that can cope with the rise in temperature up to a certain threshold through vasodilation and sweat evaporation (Kilbourne 1992). Experimental data has been used to describe various thermal indices (Quayle and Doehring 1981), and to set critical occupational and other standards to limit heat exposure and associated health effects (Parsons 2014). Although extensive research has been done on the physiological effects of heatwaves, still, there is a lack of evidence of heat tolerance in women, the elderly, and people with chronic illnesses. High temperatures can cause clinical symptoms such as heat strokes, syncope, and convulsions (Noji 1997). Severe heatstrokes can occur when the body temperature exceeds 103 °F and causes multiple organ failure. The death rate from heatstroke is very high, and it progresses very quickly (within a few hours). In survivors, permanent damage to the organ system (Dixit et al. 1997) can lead to severe dysfunction (Dematte et al. 1998) and increase early death risk. In August 2003, the French heatwave caused 14,802 deaths within 20 days (Hemon and Jougla 2004), while a major Athens heatwave in 1987 caused more than 2,000 deaths (Katsouyanni et al. 1988). Other heat waves that have been extensively studied include several heat waves in the American.

Midwest, notably the Chicago incident in 1995 (Klinenberg 2015). Unfortunately, until recently, Europe or the US had not established best practice guidelines.

Major heatwave events are also linked to other health risks, such as air pollution incidents, forest fires, and water and electricity disruptions, affecting health policies. The excessive death rate caused by the heatwave event is a short-term increase in the number of deaths, and the maximum death rate is similar to a severe pollution event (Jankowski et al. 2006). Therefore, the estimated number of casualties depends on the definition of high-temperature episodes (Fig. 1) (Pan et al. 2016). It has been found that the overall impact of a heatwave event depends on many factors, including the size of the heatwave, time of year, population experience with the heatwave event, and public health responses (Koppe and Jendritzky 2005). Most heatwave studies consider the impact on mortality, as daily mortality data is usually readily available in high-income countries. Heatwaves are also related to the increase in the number of emergency rooms in hospitals (Johnson et al. 2005; Kovats et al. 2004; Semenza et al. 1999). During the heatwave of August 2003, the number of hospital stays increased in Spain (Cajoto 2005) and France which also overburdened many hospitals (Lecomte and de Penanster 2004; Vanhems et al. 2003). The increase in fever-related hospital emergency admissions was at a specific endpoint, particularly noticeable in kidney and respiratory diseases, especially in the elderly (Kovats et al. 2004).

Higher temperatures are not associated with cardiovascular diseases (Kovats et al. 2004; Panagiotakos et al. 2004) although they have significant effects in the USA (Schwartz et al. 2004). Health system factors such as the admission threshold can explain this difference. Research so far shows that the increase in hospital admissions during the heatwave is not as substantial as the mortality data. One of the reasons may be that the person who died in the heatwave died suddenly or did not

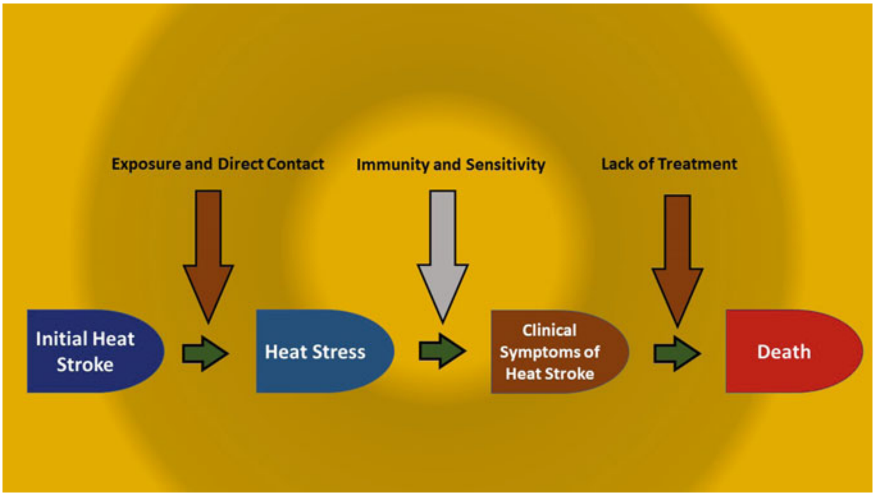

Fig. 1 Extreme impacts of heatwaves (heat stress and strokes) on the human body

attract medical services' attention. The latter assumption has implications for health protection measures.

4.2 Heatwaves as a Hazard

Ecosystems, human mortality and morbidity, and regional economies are significantly affected by the extremely high temperatures associated with heatwaves (Koppe et al. 2004; Meehl and Tebaldi 2004). Over the past decade, heatwaves have become a severe threat for human deaths in Europe (EEA 2010). European heatwave caused excessive (70,000) deaths in summer, 2003 (EEA 2010), and France alone faced 15,000 deaths by these heatwaves (Siebielec et al. 2016). Soil moisture was lost rapidly in spring 2003 due to insufficient rainfall (Ciais et al. 2005; Zaitchik et al. 2006; Fischer et al. 2007) was the hottest season in Europe, since 1500 (Luterbacher et al. 2004). In the warm climate of the future, the heat waves appear to be more frequent, long-lasting, and more intense (Meehl and Tebaldi 2004; Luber and McGeehin 2008).

5 Urbanization and Heatwaves Aggravating Factor: Urban Heat Islands

Urban communities and other ecosystems are vulnerable to the increased impacts of heatwaves. Urban development change a country's surface and create a unique urban climate (Grimmond et al. 2004) that increases the heat storage capacity by transforming the ecosystems into buildings and other infrastructure (Luber and McGeehin 2008). The accumulated and impervious surface is another powerful absorber of heat in the urban areas (Leuzinger et al. 2005). From these areas the radiations are slowly re-emitted in the form of long-wave radiation, which leads to the warming of the boundary layer of the urban canopy atmosphere (Oke 1988) known as urban heat island effect (Joehnk et al. 2008). This effect is related to the temperature difference between the city and the surrounding rural areas. A large number of buildings and population causes the increase in temperature difference of urban heat island drops in Europe (Koppe et al. 2004). The high urban temperature may cause many fatalities and morbidities (Clarke 1972). A relationship between the microclimate, demographics of urban residential areas in Phoenix, Arizona, studied by Harlan et al. (2006), observed that the thermal environment regulates the microclimates and other climatic conditions that humans have to deal with. Facts have shown that communities with open cooling functions have almost no open and green spaces, which helps increase the impact of urban heating (Parmesan et al. 2000). Hence, demographic characteristics, community environmental quality, and heatwave mortality are spatially related (Harlan et al. 2006).

6 Climate Regulation

The city temperature that is usually higher than the ambient temperature, results in a more significant impact of extremely high-temperature events. Urban ecosystems help reduce the effects of urban heat island (Bolund 1999), e.g., urban forest representing all vegetation in urban areas (McPherson et al. 1994) playing a significant role in regulating the climate, energy, and water between soil and atmosphere (Zaitchik et al. 2006). Researchers believe that greening can cool the environment at the local level (Oke et al. 1989; Akbari et al. 2001; Bowler et al. 2010) and can mitigate the effects of heatwaves. This is because plants and trees regulate the temperature through evapotranspiration. Further, green vegetation absorbs up to 90% of the photosynthetic radiation while, reflects almost 50% of the radiation in the near-infrared (Braun and Herold 2004) thus absorbs less heat than the built infrastructure (Leblanc et al. 1997). While it is not clear whether there is a minimum size threshold or whether there is a simple linear relationship between these two factors, the size of the green space affects the size of the cooling effect. On an average, the cooling rate of city parks is around 1 °C, instead of an independent green location (Bowler et al. 2010), e.g., Gomez et al. (1998) observed that in the green area, the maximum temperature in the Spanish city of Valencia fell by 2.5 °C. Wong and Yu (2005) observed that the most considerable difference in the planting area between Singapore and the central business district was 4 °C, while Hamada and Ohta (2010) showed that the temperature difference between the city and the green spaces from Nagoya in Japan is great. At the highest temperature, the difference between deciduous and mixed forests is greater than that of coniferous forests. Conversely, coniferous forests' difference is greater at the lowest temperature (Renaud and Rebetez 2009).

Alexandri and Jones (2008) suggest that for cooling purposes it is effective to place vegetation in urban structures' architectural space (Shashua-Bar and Hoffman 2003) and the cooling effect is mainly determined by the number and degree of partially shaded areas. In Athens, for example, the highest cooling effect during the brief hot weather in 2007 was 2.2 degrees Celsius on streets with higher shadows and little traffic (Tsiros 2010). Akbari et al. (2001) estimated that implementing heat island mitigation measures (e.g., tree planting) could avoid 20% of cooling needs in the US. In general, frequent use of green spaces promotes people's well-being, especially during heatwaves (Rebetez et al. 2006). This can be explained by green spaces' ability to provide better thermal comfort (Lafortezza et al. 2009).

7 Air Quality Regulation

Air quality plays a vital role in heatwaves and can cause diseases in people through these dangerous events. These circumstances create great heat and air contamination pressures, particularly in individuals with cardiovascular and respiratory diseases (Piver et al. 1999). For example, in the Netherlands, an estimated 1,000 to 1,400 people died in the 2003 summer from high temperatures, concentrations of ozone (O_3), and particulate matter (PM_{10}) (Fischer et al. 2004). In France, the relative contribution of O_3 and temperature to the high death rate during the 2003 heatwave was heterogeneous between cities (Siebielec et al. 2016). For the nine cities considered in the study, every increase in O_3 concentration of 10 $\mu g\ m^{-3}$ increased the death risk (Siebielec et al. 2016).

Specifically, during 2003, the additional risk of death due to O_3 and thermometers was between 10.6% in Le Havre and 174.7% in Paris (Filleul et al. 2006; Siebielec et al. 2016). In Croatia, a large part of the excessively high mortality rate over the same period was attributed to PM_{10} and O_3 in the air (Alebić-Juretić et al. 2007). Trees can act as biological filters due to their large leaf area and physical properties. These can remove many particles from the air and improve its quality (Beckett et al. 1998; Nowak et al. 2000; Brack 2002; Jim and Chen 2008; Escobedo and Nowak 2009). Trees can effectively reduce the effects of harmful forms of particulate pollution (such as PM_{10}) or gases like SO_x, NO_x, CO and CO_2 and effectively reduce the concentration of O_3 (Nowak et al. 2000). The ecosystem service's efficiency depends on the types of plants, the canopy area, the types and characteristics of air pollutants, and the native meteorological environment. Larger trees remove and stock more carbon dioxide from the air, capture air pollutants, provide shade, and intercept precipitation (Brack 2002).

In urban areas, areas with more urban trees absorb more pollutants from the air, and this capacity increases as the trees reach their final size (Jim and Chen 2008). In general, when the surface of the leaves and bark of the tree is rough or sticky, the tree becomes more efficient at absorbing particles (Escobedo and Nowak 2009). For smaller particles, the most effective absorption occurs in conifer needles. Because of the larger total surface area of needles, conifers' filtering capacity is greater than that of deciduous trees (Escobedo and Nowak 2009). This ability is more significant because the needles do not fall off in winter when the air quality is usually at its worst (Bolund 1999). According to Jim and Chen (2008), most of the removal work takes place in winter, which is mainly due to the higher concentration of contaminants (Bolund 1999).

Compared to smaller trees in the landscape, seasoned trees usually bring more benefits to society because they store large amounts of carbon in their tissues due to their huge size. Similarly, trees near busy roads trap more material than rural trees (Beckett et al. 1998). In Chile, for example, studies have shown that Santiago's urban forests can effectively remove PM10 (Escobedo and Nowak 2009). Likewise suburban vegetation in the Madrid region is an O_3 sink. Nowak et al. (2000) simulated the effects of increased urban tree cover in Washington DC on O_3 concentration and observed that urban trees usually reduce urban O_3 concentration. Few studies link urban forest structure and socio-economic activities with pollution dynamics in specific areas (Escobedo and Nowak 2009).

8 Climate Change Impacts: Changing of Weather Patterns in Pakistan

Due to changing precipitation patterns, Africa experienced the historical droughts, and food insecurity (Williams and Funk 2011). Like Africa, destruction in Indian northwestern part was also due to climate change, and it is now causing similar changes in Pakistan (Rodó and Comin 2003). Geographical location and climate of South Pakistan is considered as an arid region where drought and water shortages are expected to occur. Precipitation is expected to be lowest in some areas, with rainfall estimates of less than 10 mm. The country's annual average precipitation is expected to be less than 40 mm. Negative impacts of climate damage on its economic structure and population can be seen in countries like Pakistan (Qureshi and Ali 2011). Being aware of the problem and its future consequences on the economy and social development, the government of Pakistan is taking steps to overcome its possible impacts.

Although Pakistan lacks the modern technologies, infrastructures, methods, and systems for ecological development, regulators suggest investing significant resources to alleviate and adapt to climate change is a hope. However, government agencies should ensure that investments are made in building reliable irrigation systems to accommodate expected changes in rainfall. Over the past two decades, the incidence and extent of severe climate change has increased and currently Pakistan's significant portion of the population ($\geq$40%) is suffering from droughts, storms, and erratic rainfall (Hussain et al. 2020, 2010). It is expected to exacerbate in the form of unstable weather, cyclones, storms, droughts and floods (Ullah et al. 2018).

9 Adaptation and Mitigation Strategies in Pakistan

Pakistan is among the top climate change vulnerable countries in recent times, so the socio-economic development of Pakistan to adapt to the impacts of climatic conditions is essential. Pakistan's Ministry of Climate Change (MoCC) is taking various measures to help residents adaptation to national climate policies and take mitigation/adaptation measures in the areas of transport, agriculture, animal husbandry, energy, forestry, urban planning, and industry (Lin and Ahmad 2017). Based on the expected National Determined Contributions (INDC), Pakistan needs about 7014 billion$/year for mitigation measures. According to the "Green Pakistan Plan", around 1285 million rupees have been allocated to the forest department for massive tree plantation (GOP 2020). Water and agriculture are the two most vulnerable areas and adaptation measures need to be taken up in these areas. The preferred technologies recommended by the agricultural sector for rainwater management are highly efficient irrigation systems (drip irrigation), drought-tolerant plant varieties, climate forecasting and early warning systems (Ministry of Climate Change 2020).

The different departments at micro-level urgently need multi-layered and detailed strategies for climate change mitigation (Shaffril et al. 2018). Adaptive measures are needed for making less interference in forests, glaciers, wetlands, and pastures. To accomplish the national sustainable development goals, it is necessary to organize and define related processes critical to containment and adaptation.

10 Conclusion and Future Perspectives

Global warming can be seen as the impact of climate change which is the primary concern for researchers in the contemporary times. Increase in global temperature, due to increased greenhouse gases cause intense heatwaves and subsequently large number of deaths each year in several countries, including Pakistan. Pakistan's adaptability is poor due to high levels of poverty, poor economy and lack of material resources. Pakistan is vulnerable to severe and common extreme climate change effects.

First, the role of government must be actively played to remove contradictions and ineffective technologies in strategic planning, definition, and implementation. Second, for mitigation and adaptation of climate change, to prioritize and review environment friendly and sustainable processes a sustainable national development plan should be framed. Third, in addition to government intervention, people should have complete awareness, understanding, of climate conditions, which may encourage their greater participation. Fourth, government agencies, organizations, and people should concentrate to reduce the destruction of fertile lands, oceans, pastures, forests and wetlands, which are the natural sinks of pollution and policies should be formulated for their conservation. Finally, qualitative research should be undertaken to thoroughly analyze and explain the impact of climate change. Current research is focused on specific features; it is also recommended that a more in-depth assessment of various climate-related sectors be carried out. However, there is a lack of detailed studies on the sectoral causes and effects of climate change.

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Impacts of Climate Change on Agriculture and Horticulture

Mounes Sadat Eftekhari

Abstract Temperatures have risen by 0.9° since the nineteenth century, mainly due to greenhouse gas emissions. According to estimates, by 2050, this temperature increase will be around 1.5 °C or even higher. Climate change affects crop and livestock production, hydrological equilibrium, and other components of farming systems. Given the fundamental role of agriculture in human well-being, federal agencies have expressed concerns over the potential effects of climate on agricultural productivity. The agricultural sector's impact on climate change and global warming is through greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Methane gas has the most significant potential for global warming, which is about 300 times more than carbon dioxide. WMO forecast models say by 2100, air temperature will increase by 2–5 °C. Climate change is experienced at high latitudes due to rising temperatures, longer growing seasons, plant densities, increased photosynthesis, and improved crop yields. At lower latitudes, rising temperatures create environmental problems such as drought stress and limited crop yields.

Keywords Forecast models · Crop yield · Agricultural productivity · Climate change impacts

1 Introduction

Development of human civilization, change of lifestyle, and industrialization of societies followed by the excessive use of fossil fuels are the factors that have caused pollution in nature. On the other hand, the increasing growth of factories and industries and the change in land use have exacerbated the pollution level. Although the trend has been almost constant, the average alteration rate has increased dramatically over the past 100 years. Temperature has risen by 0.9° since the nineteenth century, mainly due to greenhouse gas emissions, and according to estimates, by 2050, this temperature increase will be around 1.5 °C or even higher. Greenhouse gas emissions and climate change are among the most essential concerns in the world today,

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leading to changes in ecosystems and the characteristics of the world's different biomes. Thus, extensive research has been conducted in this field to investigate the effects of climate change on various sectors such as agriculture, horticulture, irrigation, economy, natural hazards, transportation, air pollution, and security and military issues (Aroara 2019).

Given the fundamental role of agriculture in human well-being, federal agencies and others have expressed concern about the potential effects of climate change on agricultural productivity. It affects crop and livestock production, hydrological equilibrium, and other components of farming systems. However, understanding the nature of these biophysical effects and human responses is a complex and challenging task. For example, crop yield is directly affected by change in temperature, rainfall, the severity of natural disasters such as droughts, floods, and storms. At the same time, carbon dioxide plays an essential role in plant production. Therefore, to study this issue, in addition to identifying the effects of climate change on agriculture and horticulture and ways to control it, special attention should be paid.

2 Greenhouse Gases, Global Warming, and Climate Change

The Earth's atmosphere combines different gases and airborne particles (solid particles and suspended liquids) and surrounds the Earth like a thin membrane. The constituents of the atmosphere are nitrogen (N_2), oxygen (O_2), argon (Ar), carbon dioxide (CO_2), neon (Ne), helium (He), hydrogen (H), krypton (Kr), xenon. (Xe), methane (CH_4), and ozone (O_3). Among these gases, carbon dioxide, methane, nitrous oxide, ozone, halocarbons, water vapor, and other rare gases are considered greenhouse gases, and an increase in their amount leads to disruption of atmospheric compounds and thus global warming. These gases act like a glass against the short waves (radiation) of the sun entering the Earth and pass them toward the Earth but prevent the Earth's long waves (reflection) from leaving the Earth's atmosphere. So, the heat-trapping mechanism is considered as greenhouse effect. In total, it can be said that over the past 2 billion years, the climate has experienced alternating periods of heat and frost. Although the climate has been relatively stable in the past 10,000 years, global warming has been observed in recent centuries due to greenhouse gases (Qiyasi et al. 2016).

Studies show that the climate has become warmer in all seasons and most areas than in the last century. This change has had the highest temperature during the previous 50 years, the leading causes of which can be increased greenhouse gases, solar radiation intensity, suspended sulfate particles, land-use change, and the impact of human activities. The chart below shows the trend of temperature increase from 1880 to 2020. If the warming trend continues, the possibility of repeated torrential rains and other natural disasters will increase (Maleki 2017) (Fig. 1).

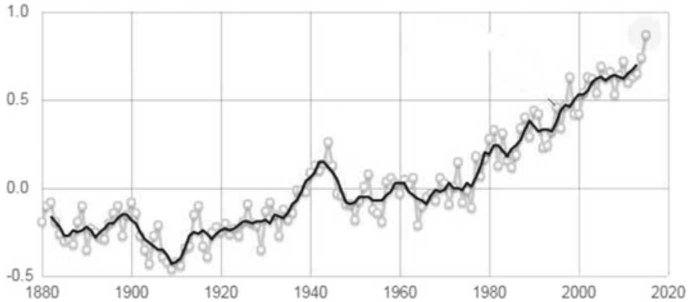

Fig. 1 The trend of increasing global temperature changes

3 The Effects of Heat Caused by Global Warming

Warmer global conditions and rising average annual temperatures because of greenhouse gases increase potential evapotranspiration in soil and plants, and therefore affect plant growth and hurt agricultural production. They also increase evaporation and plants' water needs and put additional pressure on available water resources. Marginal lands and borderlands adjacent to arid and desert regions are likely to suffer more from drought and dehydration than other areas. This is because these areas' plant species are more vulnerable due to the existing climatic conditions and the overstressed water resources (Maleki 2017; Arora 2019). Decreased rainfall limits the crop rotation options and makes planting some rain-fed crops uneconomical (Westcott 1991). Although heavy and sometimes untimely heavy rains may provide an excellent opportunity to extract and store water in some conditions, it can potentially cause flooding, intensify soil erosion, and increase soil degradation. Sometimes, untimely summer rains increase the humidity and the subsequent fungal diseases and illnesses. In some vegetation and some agricultural products, fungi and the related infections significantly reduce the yield (Qiyasi et al. 2016).

4 Climate Change and Its Impact on Water Resources

There is no doubt in the fact that today water and the resulting crises are a vital issue both at regional and global levels. Water scarcity is a critical issue in countries like Iran, which has arid and semi-arid regions. So far, many glaciers have disappeared due to climate change and if this decline continues at the current rate, most of the glaciers that feed several rivers in the warm season will disappear by the next 10–15 years.

On the other hand, due to sudden melting of snow and ice in the spring, there occurs an increased incidence of floods and droughts. In water-scarce countries, climate change reduces the snow reserves in the mountains and, makes permanent rivers seasonal, besides resulting in severe water shortages in the warmer seasons. For example, a 2° rise in temperature and a 10% decrease in rainfall in an area can reduce a river's flow by 50% or even more (Maleki 2017). If the river water is the only source of agricultural irrigation in that area, the effects are more dire. Climate change also has an indirect effect on groundwater in terms of the rise or fall of groundwater aquifers, e.g., in arid countries such as Iran, due to the all-time deficit of groundwater reservoirs, the possibility of using groundwater even in times of drought remains limited.

5 Relationship of Climate Change with Agriculture

Climate is considered as the most important agricultural production factor, as it affects the hydrological balance, and other components of agricultural systems like precipitation, soil moisture, temperature, and sea level. In turn, the agricultural sector also affects the climate system through the production of greenhouse gases such as carbon dioxide, methane, and nitrous oxide during various processes and crop production stages. Among the different greenhouse gases produced from this sector, methane gas has the most significant global warming potential of about 300 times more than carbon dioxide and 20 times more than nitrous oxide. The primary sources of methane production in agriculture and horticulture are nitrogen fertilizers, rice fields, soil erosion, biomass burning, livestock production, deforestation, wetland drainage, and straw burning (Rezaei and Afroozi 2015).

According to the World Meteorological Organization's (WMO) comprehensive forecast models, by 2100, the air temperature will increase by 2–5 °C (depending on the region), which will increase the rate of evapotranspiration by 30–40 percent especially in latitudes below 45° (Maleki 2017). As a result, areas around the Earth's dry belt, including Iran, Afghanistan, Pakistan, and African countries, will experience droughts, floods, fires, and other natural disasters. However, areas covered with snow and ice at higher latitudes, such as Russia and Scandinavia, will benefit from climate change and rising temperatures. Thus, increasing the temperature to a certain extent in different areas can have positive or negative effects depending on the place's general conditions. Climate change is experienced at higher latitudes due to rising temperatures, longer growing seasons, plant densities, increased photosynthesis, and improved crop yields. While at lower latitudes rising temperatures create environmental problems such as drought stress and limited crop yields, in temperate latitudes, with increasing temperature, the issue of spring plants, and their germination in spring, and subsequently, their decreased yield is experienced (Rezaei and Afroozi 2015). Some areas, such as those around the Earth's arid belt and areas that are still experiencing rainfall shortages, will undoubtedly experience crop declines due to reduced rainfall or increased evaporation.

6 Possible Reactions of Agricultural Ecosystems to Climate Change

6.1 Effects of Increasing Carbon Dioxide on Crop Growth

Different plant species show different responses to this phenomenon, e.g., the C_3 plant like wheat, rice, and soybeans react quickly to increasing CO_2 concentrations, while the reaction of C_1 plants like corn, sorghum, and millet is absolutely different from that of the first group. Although at the current concentration of carbon dioxide, the photosynthetic efficiency in C_1 plants is higher than in C_3 plants, these plants' reaction to the increased carbon dioxide concentration is less. Excessive accumulation of CO_2 in the atmosphere closes the pores of plants, reduces the absorption of gases, and reduces the vapors in these pores. Therefore, if carbon dioxide is saturated, crops are likely to consume less water and produce more carbon hydrates. This dual effect is expected to improve water use efficiency (relative to plant biomass to water consumed). Simultaneously, rising temperatures, changing rainfall patterns and soil moisture, and increasing occurrence of extreme weather events due to climate change enhance or neutralize the beneficial effects of growing gas concentrations on crop physiological performance (Adams et al. 2018).

6.2 The Effect of Increasing Temperature

In the middle and high latitudes, global warming prolongs plants' growth period and accelerates plants' germination, seed development, and harvesting season. As a result, arable lands in Canada and Russia are likely to expand polewards. Due to the lack of soil nutrients at higher latitudes, crop yields in these areas will be lower than in other areas. When the latitudes become warmer, the amount of carbon dioxide emitted by the plants' respiration increases, resulting in optimal growth conditions. When the temperature rises to the optimum level for plants' biological activities, most of them react negatively and experience a sudden decline in growth and reduced yield. In many climate change models, it is predicted that the minimum evening temperature will increase more than the maximum daytime temperature. The occurrence of temperature stress during daytime has a less adverse effect than increasing the average night temperature. A substantial impact of rising temperature is accelerating the plant's physiological activities, thus accelerating its maturity and development, and reducing crop yield. Further, as the temperature increases, the soil moisture retention capacity is also affected. Rising temperatures in some seasons may damage some plants (Arora 2019), e.g., extreme heat in spring and summer may cause some plants to overheat and affect grain protein production. Some of the currently thriving arable lands may gradually become marginal and low-yielding due to increasing temperatures.

6.3 Soil Erosion and Fertility

Rising temperatures due to climate change also affect the soil. In warmer climates, the rate of decomposition of soil organic matter may increase and cause other reactions to have some adverse effects on soil fertility. Therefore, the need to increase the use of chemical fertilizers to compensate for this phenomenon and prevent a decline in crop yield becomes another consequence of increasing temperature and concentration of carbon dioxide. Expanding the use of chemical fertilizers further harms water resources and air quality. Soil moisture reduction due to increasing temperature reduces root growth and decomposition of organic matter and intensifies wind erosion. Intensification of heatwaves and atmospheric pressure and humidity enhances the monsoon rains in the tropics, to increase the process of soil erosion (Aghaahmadi and Asadikani 2016).

6.4 Pests and Diseases

As the world becomes warm, the conditions become feasible for harmful insects to multiply. Further, prolonging plant growth seasons cause more of these pests (such as locusts) to go through their reproductive cycle. In areas where the intensity of winter cold does not allow insect larvae to flourish, global warming facilitates this phenomenon. It increases the possibility of pest outbreaks in the warm seasons of the year in these areas. Changing the wind patterns also changes the transmission of insects, bacteria, and disease-causing fungi. Temperature changes disrupt the proper time of the evolutionary cycle of insects and host plants, which disrupts their interaction. Therefore, the need to use pesticides in these conditions increases, and the need to develop integrated control methods becomes much more severe (Mikoyan 2015).

6.5 Rising Oceans

By the middle of the next century, melting polar ice caps and glaciers due to climate change will raise the level of the oceans and seas by 0.1–0.5 m. Rising sea levels will pose a severe threat to agriculture in low-lying coastal areas due to the intrusion of saline water into the surface and groundwater resources and subsequent disruption of the irrigation water supply from these sources (Adams et al. 2018).

7 Some Possible Options for Adapting to Climate Change Conditions

According to the issues mentioned above, one of the existing solutions to reduce the harmful effects of climate change on agriculture is implementing some possible options that can make agriculture and horticulture compatible with climate change. These solutions are as follows:

1. Application of technical methods for better use of soil moisture.
2. Soil moisture profile management in response to the risk of reduced rainfall.
3. Attention to early planting and using cultivars with shorter growth periods.
4. Improving tactical responses to planting position, based on seasonal landscape and other performance estimation information such as soil moisture storage status and planting time.
5. Maximizing water use and soil moisture efficiency by different farm management techniques including no-till operation, the return of crop residues, the spacing of rows, and the reduction of seed amount.
6. Monitoring soil moisture to ensure optimal irrigation and management practices.
7. Planting, holding, harvesting, and paying attention to planting cycle, weed control.
8. Planting annual plants with deeper roots (wherever possible) because they can improve water productivity and absorb moisture adequately.
9. Increased use of forage plants after summer rains.
10. Reducing the possibility of soil degradation and erosion.
11. Building new dams to store heavy rainfall and showers.
12. Decreasing crop yields in marginal areas by making certain necessary changes in agricultural systems.
13. Switching to animal husbandry may be considered (although it should be noted that livestock breeding would also be affected by climate change).

7.1 Compatibility Options

Each field should be evaluated for planting suitable species, and in marginal areas, risk assessment should be performed to determine the degree of flexibility and stability.

7.2 Soil Management

Effective soil management in farming activities improves soil conditions. It increases the yield of crops that reduce greenhouse gas emissions and improves environmental sustainability.

7.2.1 Possible Effects

Excessive (non-optimal) nitrogen use can lead to more losses through leaching (deep infiltration) and runoff. In heavy rainfall, increased leaching of fertilizers and plant nutrients leads to reduced soil quality. Reduced rainfall reduces vegetation and increases the likelihood of wind and water erosion. Soil compaction or submergence causes favorable anaerobic conditions for nitrogen conversion in the denitrification process wherein nitrate, a suitable form for plant consumption, will be converted to Nitrous Oxide, a non-consumable form for plants, and one of the greenhouse gases. Soil acidification may increase due to increased carbon dioxide concentrations.

8 Reduction of Greenhouse Gases

8.1 Calculating Carbon

The agricultural sector has a significant share in global greenhouse gas emissions. According to the Climate Change Division, Australia's share of agriculture (including energy and transportation) in greenhouse gas production in 2006 was about 15.6%, making it the second-largest greenhouse gas contributor in the country. The agricultural sector and forestry potentially play an effective role in reducing and controlling greenhouse gases through carbon sequestration (Aghaahmadi and Asadikani 2016). Agriculture plays an essential role in the exchange and control of greenhouse gases, both as a source of production and as a source of carbon sequestration from the atmosphere. To date, agriculture has been one of Australia's most important sectors in reducing greenhouse gas emissions. The Australian Government has exempted the agricultural sector from the plan by 2015 under a mandatory national strategy to reduce carbon pollution. According to this plan, each production or service sector is supposed to pay for the amount of carbon it produces. Each carbon-producing sector is obliged to reduce carbon production by using existing technologies and, if necessary, using alternative technologies. However, due to the importance of controlling carbon emissions, the amount of carbon production in the agricultural sector, which has a unique complexity in measuring and monitoring, is still considered as an unavoidable issue to find a suitable solution for it. Determining the agricultural sector's role in the plan to reduce greenhouse gas emissions depends on international agreements. Under the Kyoto Protocol, many governments, committed to enforcing the carbon offsets law, e.g., the Australian Government implemented a plan called the "Carbon Pollution Reduction Plan" (CPRS) to mitigate climate change effects, which has had a significant impact on the country's energy policy (Aghaahmadi and Asadikani 2016).

8.2 Management of Greenhouse Gas Emissions from Soil

Nitrous oxide (NO) is another potential greenhouse gas. According to the IPCC, nitrous oxide gas makes up to 7% of greenhouse gases. The share of agriculture in the production of this greenhouse gas is estimated at 60%. One of the reasons for its production is the high rate of consumption of nitrogen fertilizer to boost agricultural production. Most plants use only less than 50% of the nitrogen applied to the soil as fertilizer, while the rest enters the environment and creates direct environmental pollution causing the production of greenhouse gases. Plans that increase nitrogen efficiency can reduce emissions, mitigate greenhouse gas emissions, and at the same time, promote environmental sustainability and the profitability of agricultural products (Mikoyan 2015).

8.3 Effective Measures to Reduce Greenhouse Gas Emissions

- Soil and tillage management to minimize nitrogen losses.
- Excellent and adequate drainage to reduce the possibility of soil flooding and reduction of soil moisture in extreme conditions.
- Avoiding application of fertilizers to saturated soils, especially nitrate fertilizers.
- Increasing soil organic matter by placing forage plants in crop rotation and adding compost to the soil.
- Adding gypsum to soil to improve soil structure and avoid anaerobic conditions.
- Covering the soil surface with vegetation as much as possible to prevent or reduce nitrogen losses through leaching or denitrification.
- Avoiding crop residue burning and instead returning crop residues to the soil and, as far as possible, pruning instead of incineration.
- Application of nitrogen fertilizer during the growing season based on the calculation of the plant-based nitrogen requirements on the intended yield to prevent its excessive use and search for optimal consumption strategies.
- Estimation of available nitrogen before the application of fertilizers.

8.4 Managing the Emission of Methane Gas from Livestock

A huge quantity of methane gas is produced by the ruminants such as cattle and sheep; for example, as per the available statistics, methane production in Australia, where the livestock industry is booming, is about 12% of greenhouse gas emissions. Changing farm management to use techniques that further convert this feed energy into productive energy can reduce greenhouse gas emissions and improve livestock productivity. Any action on nutrition management, feed improvement, animal health, livestock management, and genetic modification can help control greenhouse gases and improve yields. Improving the quality of pastures, adding feed additives to animal feed, managing feed content, and increasing the quality and value of animal feed are the tasks that will enhance productivity and reduce methane gas emissions. The higher content of nitrate, phosphate, and potassium in fertilizers and animal waste can be due to poor and ineffective animal nutrition.

For this reason, paying attention to healthy livestock nutrition can increase the production efficiency of livestock and livestock products, help the environment, reduce greenhouse gases, and consequently reduce climate change. Animal waste is one important source of carbon dioxide, methane, and nitrous oxide. It is estimated that about 2.5% of Australia's greenhouse gases are generated through animal waste decomposition. The high level of greenhouse gases in animal waste is due to large amounts of organic matter, moisture, rejected carbohydrates, and high trace elements. So, we need to properly manage the animal wastes to avoid any additional burdens of GHG on the atmosphere.

9 Reducing Greenhouse Gas Emissions at the Farm Level

One practical way to reduce greenhouse gas emissions is to develop vegetation or afforestation that allows the plants to absorb carbon dioxide and stabilize it in the soil. Storing carbon in the soil can also help reduce the release of these gases. Trees and other plants absorb atmospheric carbon dioxide during growth and the synthesis process. Carbon is an essential element in good soils that improves soil fertility, water holding capacity, and aeration one, and facilitates nutrient mobility. It provides a favorable environment for the better establishment and growth of plants. Carbon stored in the soil reduces greenhouse gases' adverse effects compared to carbon, active in the atmosphere as carbon dioxide. Storage of carbon in the soil is one way to reduce greenhouse gas emissions and improve crop yields. In this regard, to help absorb and store carbon in the soil, the following can be considered:

- Indentification of new tree planting stations (forestry), and selecting suitable species and convenient locations for their survival and maximum growth.
- Encouraging the production and regrowth of native plant species and keeping animals away by fencing or other measures.
- Protecting native plants from fire, plowing, and destruction by animals.
- Estimating the amount of carbon that can be absorbed by forests and plants, e.g., Australia has developed a software called the Carbon Calculation Tool for this purpose.
- Selection and application of protective plowing.
- Returning crop residues to the soil and avoiding straw burning.
- Using organic animal manure to fertilize the soil.
- Avoiding soil fallows and controlling grazing to prevent the bare soil.
- Consider planting crops with annual forage plants and planting mixtures of forage plants with legumes.

Improving energy efficiency at the farm level

Improving energy efficiency in agricultural operations and using alternative fuels instead of fossil fuels will reduce greenhouse gas emissions while saving on electricity and fuel costs. In this regard, the following can be considered:

- Selection of new equipment and devices according to the energy efficiency.
- Changing the consumption from diesel to liquefied petroleum gas and paying serious attention to renewable energy sources.
- Replacing high-consumption machines with energy-efficient machines.
- Optimal use of natural light and air conditioning in livestock and poultry buildings.
- Insulating buildings, hot- and cold-water pipes, and water storage tanks.
- Installation of energy-saving lamps in farm production buildings.
- Continuous maintenance and service of machinery.
- Application of protective plowing and traffic control in large farms (reducing heavy machinery traffic on the soil surface, especially in high humidity conditions).
- Improving the efficiency of chemical fertilizers and pesticides.
- Coordinating the power of irrigation pumps with the control of their drive motors.
- Utilizing soil moisture monitoring to improve irrigation efficiency and, therefore, less energy consumption to improve irrigation water supply and distribution efficiency.

10 A Review of the Case Study of Date Palms in the Field of Climate Change and Horticulture

Considering the date palm as one of the strategic crops of Iran, many studies have been carried out on the effect of climate change on this crop. Evaluation of distribution of date palm (*Phoenix dactylifera*) in Iran under climate change conditions has been done using topographic data, soil physicochemical properties, soil classification, land use, and climatic data. Results of a number of such studies show that due to climate change, large-scale changes are expected to occur in areas suitable for date cultivation (Adhaahmadi and Asadikani 2016).

Comparison of the current distribution of *P. dactylifera* (Fig. 2) in areas with suitable soil properties in terms of physio-chemical classification, land use, and slope less than 10° in Iran shows that these areas have >20 EI (Fig. 3).

According to the results, approximately 87% of the current distribution of dates (Fig. 3) in Iran is in the appropriate range (Adhaahmadi and Asadikani 2016).

As shown in Fig. 3, the gray sections show the suitable areas for date cultivation in terms of soil physicochemical properties, classification, and land use with a slope of fewer than 10°. The results show that 4.8 million hectares of Iran's southern and central parts are currently suitable for date cultivation. The prediction models (Fig. 4) indicate that between 2030 and 2070, large areas will be prone to date cultivation. However, there are differences between the results of the models, which

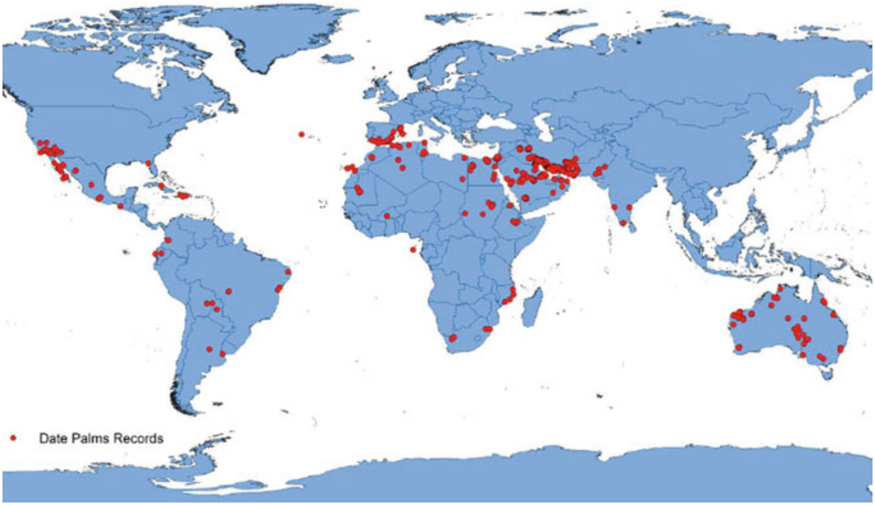

Fig. 2 Current distribution of date palms worldwide

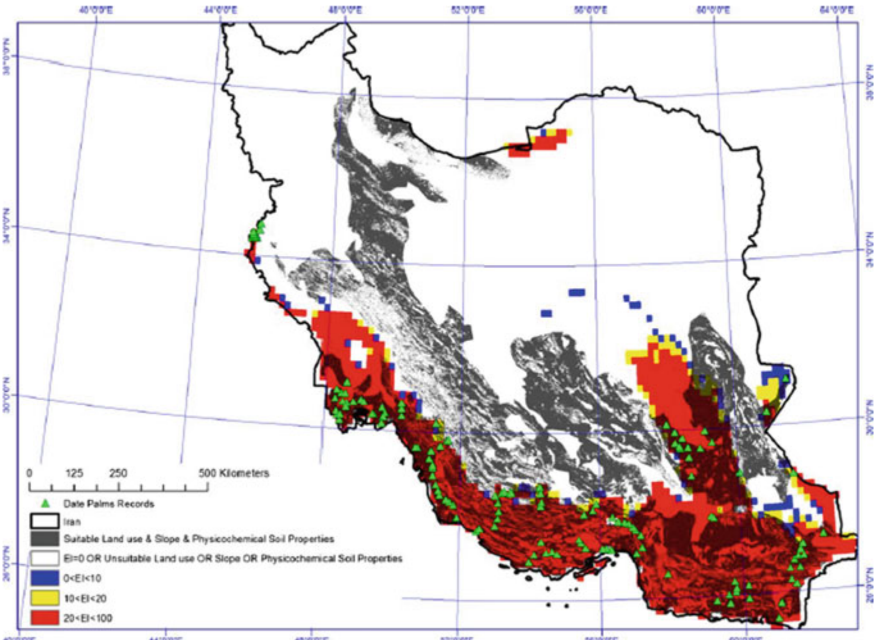

Fig. 3 The current distribution of date palms in Iran

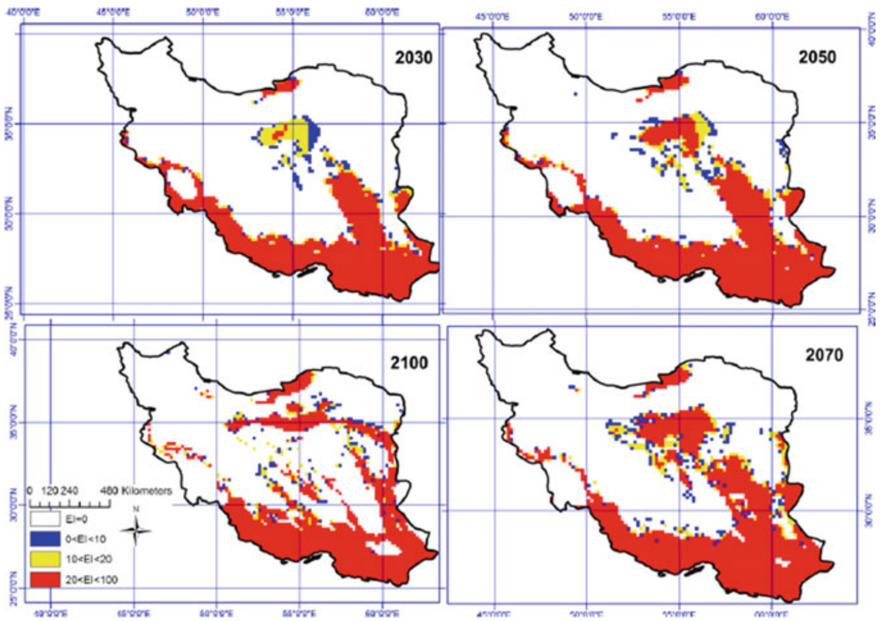

Fig. 4 Favorable areas for date cultivation in terms of climatic conditions (EI > 1) for 2030, 2050, 2070, and 2100

are expected to intensify between 2070 and 2100, due to the different predictions of precipitation and temperature changes in each model. One model predicts that by 2100 the temperature will rise by 4.31 °C, while the other model predicts this rise to be 2.11°. In terms of precipitation, one model predicts only a 1% decrease in annual rainfall for 2100, while the other model estimates this decrease at 13–15%. Both models predict that due to rising temperatures in central Iran, 5–13 million hectares of these potential areas will lose their suitability by 2100. Therefore, both models show that because of heat stress by 2100, large sections of latitudes 30–35° north and 50–60° east will be unfavorable for this crop. Further, it is estimated that by 2100 (Fig. 4), the cold stress and humidity will no longer be a problem for dates (Adhaahmadi and Asadikani 2016).

Refining the forecasting model outputs using non-climatic parameters such as desirable physical and chemical properties of soil, soil classification, slope, and land use makes the output more accurate and valid. For example, the models show that approximately 56.5 million hectares of parts of Iran will be suitable for date cultivation by 2030, while based on soil chemical-physical properties, soil classification, slope, and land use, 34.25 million hectares will be unsuitable and the same trend is observed for 2050, 2070, and 2100 in both models, shown in Fig. 5 (Adhaahmadi and Asadikani 2016).

Cultivation of dates in unsuitable soil has several consequences, e.g., it hurts the weight, size, diameter, and fruit length. Saline soils, mainly located in central

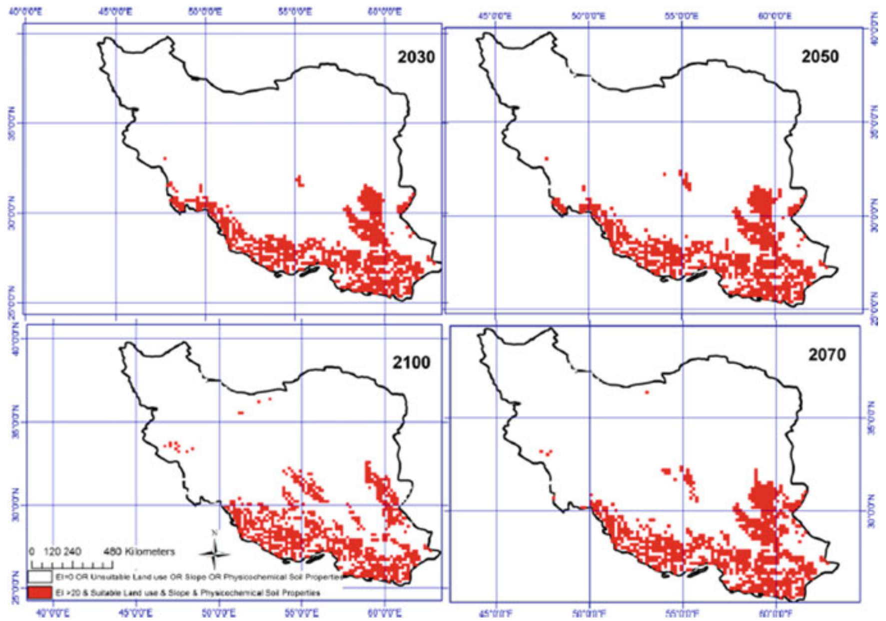

Fig. 5 Suitable areas for date cultivation in Iran for 2030, 2050, 2070, and 2100 based on the suitability of soil type, physicochemical properties of soil, and land use with a slope of fewer than 10° and EI > 20

and eastern Iran, significantly reduce soil water's osmotic potential and date yield. Another consequence of saline soils is that toxic ions can cause severe problems for plant growth besides inhibiting date palm root growth. Further, date seeds cannot germinate in saline soil. The soil map shows that most of Iran's central and eastern parts have salinities above 16 ds/m, making these areas unsuitable for date cultivation. Therefore, refining the climate model results by non-climatic factors such as soil type gives great credibility to the predictions.

11 Conclusion

Climate change has certain seriously irreparable consequences on the world's agriculture systems, damaging the crop distribution zone, crop quality and quantity, and food security. It has the potential of pushing the whole world especially the poor and developing nations into abject poverty. It renders millions of children in the developing world the prey of malnutrition, thus challenging the millinium sustainable development goals. Therefore, sustainable agricultural production necessitates accurate land-use forecasting and climate modeling, because the modeling and refining of the results enable growers to take appropriate steps to minimize climate change's adverse effects and consider the predicted scenarios in crop cultivation.

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Ecological Responses to Climate Change

Mohammad Pouresmaeily

Abstract Numerous experts believe that we are on the verge of a mass extinction, and that man-made climate change is one of the greatest threats to global biodiversity at the moment. In-depth assessments of many taxa indicate that 10–70% of plant and animal species investigated thus far may be more vulnerable to extinction as a result of climate change, and that by 2050, climate-induced habitat alterations may result in the extinction of 15–37% of species. Additionally, there is an abundance of evidence of recent climate change's ecological impacts, spanning from arctic terrestrial to tropical marine habitats. Extreme weather events elicit responses at all levels of the ecosystem, from the individual to the entire ecosystem. Flora and fauna's responses cover a diverse variety of habitats and organizational hierarchies, from the level of the individual species to the community as a whole. Recent climate change has already resulted in ecological consequences. Numerous studies have now documented ecological responses to contemporary climate change, allowing us to determine whether the magnitude and type of recent responses match projections. Additionally, this chapter examines the ecological response to the current climate change phenomenon. Additionally, this chapter examines the ecological response to the current climate change phenomenon.

Keywords Ecological response · Flora · Fauna · Extinction · Aquatic ecosystems

1 Introduction

Earth is around five billion years old, and humans began their lives, only 0.0004% of this date (approximately 20,000 years ago). During this period, some fundamental changes have taken place in the earth's climate, and some of those changes have only occurred in the last 12,000 years (Richardson et al. 2009). The relationship between climate change and the earth's surface ecosystem significantly affects the water and

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energy cycle. For this reason, today, the phenomenon of climate change is considered the most significant environmental challenge in the world.

Earth is a dynamic system in terms of its structure and geological function, and likewise, it shows complex reactions against this humanizing phenomenon. Among the possible effects of climate change and global warming on the geosphere can be mentioned: desertification, climate catastrophes, droughts, changes in the pattern of prevailing winds, and, consequently, disturbance in the habit of sea and ocean streams, land drowning, double-entry of pollutants into aquatic environments, mixing of fresh and saline water sources, etc. The biosphere- the living part of the earth that creates and sustains life, is highly subject to differences in its three major components.

Events caused by climate change, which occur on earth, also affect the earth's vast ecosphere, a vast system that creates and sustains life. According to research, some of the crucial results of climate change include massive and strong extinctions, changes in species composition, reduction of biodiversity from gene level to species and ecosystem level, the emergence of foreign and invasive species, changing migration patterns of animals, changing mechanisms of dispersal, changing distribution ranges and physical geography of species and, pollution, etc. All biological consequences are due to the alignment and integration of the effects of one or more geological, climatic, and morphological changes that enter the earth's biosphere alone or together.

Although many predictions about this phenomenon indicate its destructive effects, some studies also suggest the violent nature of the possible occurrence of adaptive processes against this phenomenon. Genetic adaptations at the level of species and populations, the continuous event of evolutionary processes during the repeated occurrence of this phenomenon over several billion years, are among these cases.

Besides, large amounts of DNA molecules in eukaryotic cells do not currently play a biological role in the genome. They are not also used in the transcription and translation process of DNA expression. However, they may function in future climatic conditions alongside evolutionary processes such as natural selection, inter and intra-specific evolutionary adaptations, and co-evolution, etc., in a large number of species. As a result, in many ecosystems, possible transformation happens in many species. However, in some cases, ecosystems may not respond appropriately to climate change and may disrupt or collapse. So, ecological responses to climate change are vital issues and challenges that need to be addressed, which requires a lot of analysis and extensive research (Emami and Saniei 2014; Faremi and Noradzadeh 2018).

So far, numerous studies have provided evidence of species' responses to climate change. Most of these studies focus specifically on individual species and show how climate change impacts species' phenology and physiology. The remarkable thing about species in the same neighbourhood or the same area is that their response to climate change is not different, so they are related in this regard. Further, sometimes, due to ecological connections between different species, climate change affects one species' individuals and affects other species' individuals in another region.

2 An Overview of the General Concept of Climate Change

Since the release of the IPCC Third Evaluation Report (TAR), climate change recognition has made significant progress over time, and the reason for these improvements include:

- Achieve a large amount of new data
- More comprehensive and sophisticated data analysis
- Understanding the complexities of climate change
- Simulation of physical processes in climate models
- Discover the range of uncertainty in these climatic model results (Richardson et al. 2009).

It is a fact that climate change is happening and will affect the planet, at least for decades to come. The extent and intensity of global warming in the twenty-first century depends on different emission scenarios. According to the IPCC's special report on various greenhouse gas emission scenarios, the average global warming from 1990 to the end of 2100 has a range of changes of 1.4° to 5.8 °C, as well as the intermediate sea level from 9–88 cm will change under the influence of thermal expansion and melting of icebergs (Emami and Samiei 2014).

The available evidence shows that climate change is undeniable. We cannot wait any longer to take action, said the former UN Secretary-General (Kofi Annan) in 2001 in a speech in the United States. Each day, there are many reasons that the climate is changing and evolving. According to the latest report released by the World Meteorological Organization, 2010 was declared the warmest year in recent history. Over the past century, the earth's temperature has risen by 0.5 °C, the most massive increase in at least a hundred years. According to the IPCC (2007), air temperatures have risen sharply in recent decades. In the last 35 years, it has increased by about 0.18° per decade, in the previous 60 years by 0.13° per decade, and over the last 160 years, it has increased by about 0.045 °C per decade (IPCC 2007).

Abnormal climatic phenomena, including thunderstorms, severe floods, and successive droughts, have been recorded in many parts of the world. Due to this increase in temperature, the snow cover level decreases; glaciers are melting, lakes and lagoons are warming, the rainfall pattern is continuously changing, sea level is increasing, and the droughts occur with greater intensity and frequency. On the other hand, these variations cause changes in the biological system of nature, apparent consequences of changes in the distribution and dispersal of plants and animals, and diversity changes.

2.1 Knowledge of Climate Change

Knowledge and understanding of climate change have increased dramatically over the past decades, which has happened slower for other science aspects. Nevertheless, climate science is changing rapidly. Over the past two centuries, scientists have become more confident in the essential elements of climate science. However, the study and research on climate systems' main factors still need more research and exploration.

For example, recent changes in the behaviour of Arctic ice masses and natural sources of carbon uptake are consistent with accelerating climate change. However, some ambiguities about climatic phenomena still need to be examined, traced, and identified to properly scrutinize and assess the degree of danger imposed by them (Pignot et al. 2007).

The IPCC's Fourth assessment report summarizes the state of climate change science up to 2006 and identifies issues with a robust scientific agreement. The main results of the IPCC's First Working Group are as follows (IPCC 2007):

- According to the available evidence and observations, global warming, rising global average temperatures and oceans, extensive melting of snow and ice, and rising sea levels are clear and undeniable.
- Long-term changes observed in many climatic parameters on a continental, regional, and oceanic scale cover some fluctuations, including changes in the Arctic ice, massive precipitation changes, increasing salinity of oceans, changing patterns of winds, unusual events such as droughts, heavy rainfall, extreme heatwaves, and the intensification of tropical storms.
- Climatic information from the past Geology reinforces the interpretation that the last half-century's heat has been unusual for at least the previous 1300 years. Of fact, in the very distant past (approximately 125,000 years ago), the polar regions were substantially warmer than they are now. Therefore, the decline in ice volume in these places due to this heat has increased sea level.
- Since the middle of the twentieth century, the most massive increase in global warming is most likely (>90%) due to the rise in greenhouse gas emissions from human activities. Human activities' significant impact has now extended to other aspects of the climate, including ocean warming, rising continental average temperatures, and changing wind patterns.
- Continued greenhouse gas emissions at or above current levels will lead to further warming and intensify many climate systems changes in the twenty-first century, which is likely to be much larger than those observed in the twentieth century (IPCC 2007).

2.2 Ecological Planets Index and Ecological Footprints

The ecological planet Index is a measure of natural ecosystems' state based on the abundance of animals and plants. Simultaneously, the Ecological Footprint Index shows the human demand for the earth's natural and biological resources. Of course, these two indicators do not cover all the necessary conditions for achieving sustainable development. Nevertheless, without being aware of the biosphere's ecological limitations, it is impossible to claim that the planet is stable.

The ecological Planet Index is a measure of the state of the world's natural ecosystems. This index is obtained by calculating the average of three separate sub-indices: the abundance of forests, access to fresh water, and abundance of aquatic animal species. The pattern of changes in the biosphere index is declining, with a decline of around 30 per cent from 1970 to 2005. (IPCC 2007).

The population of the earth's biogeographical regions in the tropics and southern temperate areas seems to be losing their biodiversity faster since 1970, while the northern temperate regions appear to be more sustainable in terms of biodiversity (Fatemi and Noradzadeh 2018).

2.3 Ecological Footprint

The ecological footprint is an indicator that shows human demand or human need for land and sea to produce the required resources and disposal of wastes generated. In 2005, researchers estimated the index's global value at 17.5 billion hectares or 2.7 ha per capita. Meanwhile, the total productive lands, or the earth's global production capacity, are equal to 1366 billion hectares or 2.1 hectares per person (Emami and Samiei 2014).

The ecological footprint compares the consumption of renewable natural resources with the bio-production capacity of nature. A country's footprint also shows various factors, including the total land area needed for agriculture, forest development, grazing, and fishing, maintaining sustainable energy consumption, and creating enough space for the necessary facilities and infrastructure of that country.

For the first time in the 1980s, human ecological footprint exceeded the earth's bioavailability, and this surplus demand has continued ever since. Previously, ecological footprints included other components, such as nuclear energy, that reflect energy production from nuclear power plants. This component is no longer considered to improve uniformity in estimating the earth's bioavailability. Of course, this does not mean that the use of nuclear energy is not safe, but it cannot be easily used for the earth's biological capacity. Most countries usually source part of their consumption from other countries; therefore, their footprint is the sum of land required to produce these resources, regardless of their geographical location.

According to the World Wildlife Foundation, the earth's production capacity is about 11.4 billion hectares, slightly less than a quarter of its area. This amount of land, which shows the production capacity, biologically forms the earth's biomass's productivity and bedrock. The other three-quarters of the earth's land area includes deserts, icebergs, frozen lands, and deep oceans, which account for the earth's relatively low biodiversity. The per capita amount of this fertile and productive part of the earth's biosphere, a quarter of the earth's area in 1999, was reported to be 1.9 hectares. At this rate, natural resource consumption in 1999 was about 20% higher than the earth's bio-production capacity. The earth's bio-production capacity and ability also vary with the amount of productive land and the average production per unit area. Hence, factors such as population change, consumption, and the level of technology can bridge the gap between the human footprint and earth's bio-production capacity (IPCC 2007; Richardson et al. 2009).

As the planet's bio-production capacity decreases due to degradation or climate change, the gap between consumption and production widens. The result of this unfortunate trend will be an increase in over-exploitation, which makes the conditions for a healthy and desirable life more unfavourable. As mentioned earlier, humans have been crossing the equilibrium since the 1980s, consuming more resources than the planet can produce. If the degradation continues, ecosystem services such as water purification, climate change, and environmental sustainability will face serious challenges. For example, tropical forests support a wide range of biodiversity and provide invaluable services to local and global ecosystems. When these forests are destroyed, their use and their diversity are endangered up to the level of extinction.

Evidence shows that the lives of living organisms are in danger due to deforestation operations, illegal logging and fires, and climate change. Between 2000 and 2005, 3.5 million hectares of Brazilian forests and 15 million hectares of Indonesian forests have been destroyed in these events. This extent of deforestation has reduced tropical forest animal populations by around 60%. Since 1970, the arid species population has declined by about 44 per cent, while dryland systems make up more than 40%, including desert ecosystems, savannas, and tropical and tropical arid vegetation (Pignot et al. 2007).

According to researchers, 20% of the dry area is at risk of degradation. Meadows are also declining both in size regarding their gradual conversion to agricultural land and terms of quality. In comparison, human life is directly (through food supply) and indirectly dependent on these areas. These areas also cover a wide range of natural biodiversity, from rare to crucial species. Further, since 1970, the people of grassland-dependent species have decreased by 36%, and several factors have been identified to destroy the grasslands:

- Natural and unnatural fires
- Livestock grazing, especially overgrazing
- Droughts
- Desertification process (IPCC 2007; Richardson et al. 2009).

3 Phenological Changes and Ecological Communications and Networks

Changes in some species' life patterns, especially in temperate climates, can function as seasonal changes. To explain it, the stages of phenological changes in several decades have been studied, and in all studies, the role of environmental conditions is shown to be prominent. For example, recent anomalies in the spring phenophases of plant and animal species significantly affect the average air temperature in spring.

In some cases, the effect of climate change on plants' spring phenology can be observed in terms of germination, leaf emergence, flowering, and fruiting. Long-term studies of the phenological trends in South America and Europe suggest that reproduction and flowering have changed in recent years due to climate change. Research shows that in Europe, leaf and flowering occur 1.4 to 3.1 days earlier in the last 30 to 48 years and in South America 1.2 to 2 days in the previous 35 to 63 years. There is some evidence of a change in fall activities that is less noticeable. Such as changes in tree leaf colour, where studies have shown colour changes in tree leaves with a progressive delay of 0.3 ± 1.6 days per decade, and some studies have reported an increase in growth length of 3.6 days per decade in the last 50 years (Fatemi and Noradzadeh 2018; Parmesan and Hanley 2015). Some species are sensitive to changes in spring temperature, wherein flowering has been seen to occur faster than usual. These species need a strategy to adapt to warm winters (false spring) before facing high spring temperatures (P.B, S.E and T.D 2014).

Also, a response threshold in spring phenology, for example, for some plant species, indicates that some species' current trend reacting to some climate changes cannot continue linearly and directly in the future. Other factors may also play a role. Thus, although there is ample evidence of phenological changes in plants and animals due to recent climate change, different species do not respond uniformly. They may have different responses to the climate and other environmental factors.

Even in cases where the climate is the dominant stimulus for species phenology change, different species may respond differently to the climatic parameters. The consequences of such a differential response are observed in the time of species interactions in environmental networks, such as food networks and parasite-host networks. In food networks, climate fluctuations affect the relative time required and food availability (Fatemi and Noradzadeh 2018).

4 The Effects of Climate Change on Morphology

The increasing concentration of CO_2 directly impacts photosynthesis, gas exchange, and other plant development processes. In C3 plants, a study in this field showed that increasing carbon dioxide concentration would increase groundwater biomass by 20%. Biomass has also grown 33% in certain circumstances, and the cause for its rise or decline relies on the quantity of nitrogen and water available (P.B, S.E and T.D 2014).

The increasing number of leaf nodes, leaf size, root length and changes in plant fertility are some of the changes reported by farmers due to increased carbon dioxide concentrations. These changes occur, especially in soybeans, wheat, rice, peanuts, and beans. The following figure shows the effects of increasing CO_2 concentration on plants. The increase in leaf size occurs due to the proliferation of cells and their development. Further, the increased concentration of carbon dioxide causes the production of new epidermal cells in the leaves. Similarly, increasing carbon dioxide

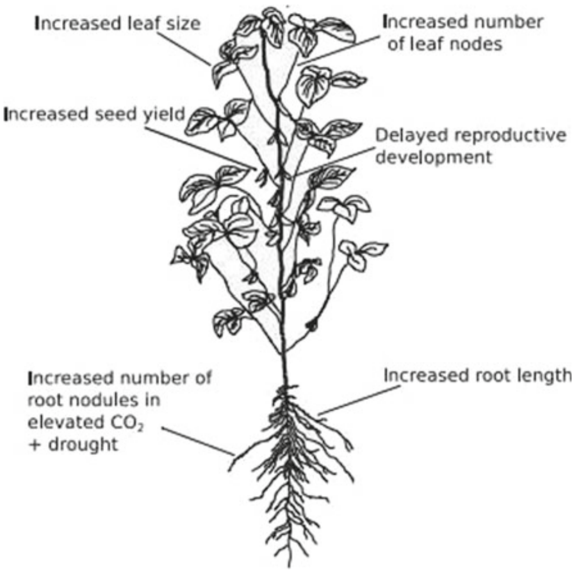

Fig. 1 Effects of increasing CO_2 concentration on growth and development of soybean plant

and reducing rainfall in soybeans increases the number of root nodes (Gray and Brady 2016) (Fig. 1).

5 Evolutionary Response of Species to Climate Change

Rapid climate change causes a wide range of pressure such as increasing heat and drought stress on populations. Differences in thermal thresholds and the emergence of stable temperatures and warmer winters will change the living Environment, which means climate change destroys natural habitat and directly or indirectly affects the entire ecosystem. Therefore, when these effects oppress a population, species invasion becomes acute, and this invasion affects species evolution and gene change in itself. The ecosystem will face the introduction of new population genotypes. Although there is clear evidence of genetic modification in natural populations, it does not necessarily support climate change.

In a study on B. Pubescens and Betula Pendula, genetic changes in these two plants were investigated. This study showed that the species' population levels significantly evolved with changing climatic conditions, especially for the reproductive rate. Adaptation to future climatic conditions requires the simultaneous development of several different plant traits correlated with each other. Therefore, diversity is the essential condition for plant survival in the face of climate change. Plants with lower genetic diversity, slower development, and lower fertility than other species populations are prone to failure and extinction. A plant population's potential to adapt to climate change depends on its life span and the age at which it reproduces. If the conditions are the same for perennials and annuals, perennial species adapt more quickly to environmental changes (Anderson et al. 2012) than animals.

6 Species Migration

One of the effects of climate change is the species' geographical range and migration to new geographical areas. Evidence of these shifts has been observed in different species during the climate change period. For example, warm-water species found in the Mediterranean and northern regions in 2002 or thermophilic plants scattered around their local habitat. Studies even indicate Antarctica's plant diversity has increased by 50 per cent or more in the last two centuries (Huanga 2020).

Today, many studies have examined the effects of climate change on plants, invertebrates, birds, fish and their relocation to new lands. They found that the arrival of new species had a different impact on local communities, divided into two categories. The first category is non-native species, which are, in fact, species with a mechanism similar to local communities that reproduce in new habitat conditions and the second category, invasive species whose entry into a new geographical space causes adverse effects on local communities. Therefore, it is expected that the plant community will also change with the introduction of new species. In the Sonoran Desert in the southwestern United States, wood species density, loss of local species, and increased animal species previously known as rare in the region have been observed (Tubridy 2020).

7 The Response of Ecosystems in Different Environments to Climate Change

As climate change is variable, it can have other effects in different environments. The following figure is an overview of the responses of ecosystems in different environments to global warming.

Controls of Antarctic soils by utilizing Perspex cloches given reasonable reenactments of climate alteration (temperature increment and introduction to distinctive wavelengths of UV radiation) using diverse Perspex sorts, VE, and Bull. These driven inside two a long time to an expanded differing quality in soil nematode communities (colours demonstrate the corresponding commitment of major genera), comparable to that found in more created microhabitats (c). Nevertheless, the expanded event of dying occasions on coral reefs (d) will likely diminish wealth on the off chance that not differences (Walther GT et al. 2002) (Fig. 2).

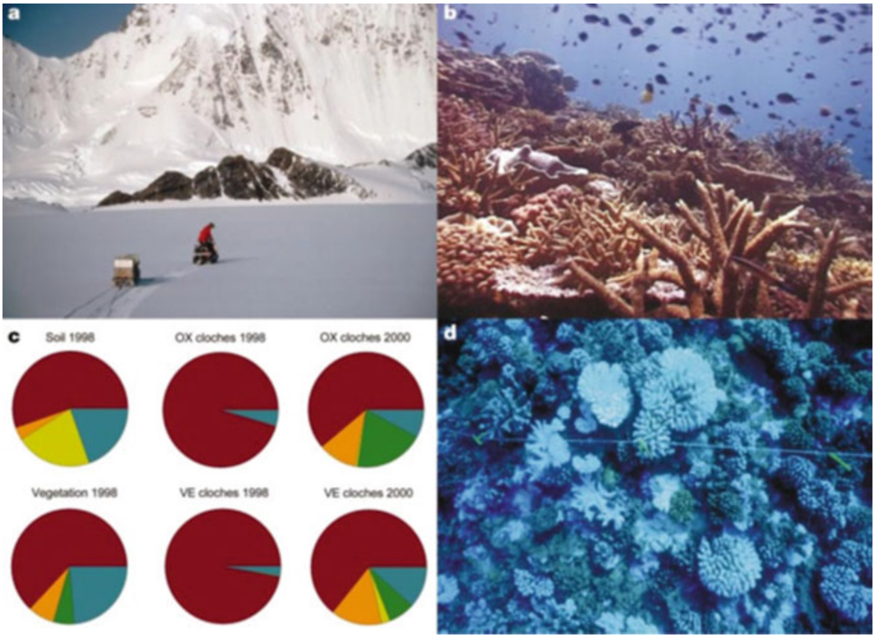

Fig. 2 Various environments and their responses to global warming

7.1 The Influence of Climate Change on Forest Ecosystems

Forests provide various functions, including protection of water, soil, biodiversity, conservation and improvement of water quantity and quality, landscaping, wood production, non-wood products, and recreation. Climate change affects forests' structure and functions and poses many threats to them, such as fires, the spread of pests and diseases, human intervention and development, and droughts.

Climate change has direct and indirect effects on forests' growth and productivity, directly impacting changes in carbon dioxide in the air and an indirect impact through complex interactions in the forest ecosystem. Climate change forecasting provides a reasonable estimate of land development, fire suppression, and air purification for forests. The continuous trend of these changes in the future is likely to jeopardize some of the forest's valuable goods and services (Ramezani et al. 2018).

7.1.1 The Impact of Climate Change and Dust on the Productivity of Forest Ecosystems

Many climate changes are likely to affect tree growth and productivity. These effects become more pronounced with increasing carbon dioxide levels and air temperature, and changes in rainfall regimes. Because of global warming, the temperature also rises with the growing season, but with this global warming and increasing temperature, the range of distribution changes. Climate change also increases the risk of droughts. Although many trees are resistant to some degree of drought, it is likely that in the future, droughts will be more severely affected by climate change than in previous periods. Furthermore, this will increase the risk of fire, aggravation of diseases, and pests for trees (Ramezani et al. 2018).

Dust particles (less than 10 microns in diameter) can have potentially harmful effects on plant communities. Dust deposition on the branches and leaves of trees can reduce photosynthesis and bury the buds under the dust. It also reduces the differentiation of vegetative buds and facilitates growth in the following year.

Dust particles can be deadly to the tree by closing their stomata, reducing photosynthetic activity, leaf fall, and tissue death. The reduction of photosynthesis decreases light intensity to the leaves' surface, and the growth rate decreases due to this phenomenon. Any viscous or absorbent substance placed on the leaf causes dust particles' accumulation and reduces photosynthesis, leaving small leaves. Dust particles less than 0.05 mm in diameter disrupt the mechanism of the pores, which are mainly responsible for two significant and vital activities, namely respiration and transpiration. Closure of pores by tiny dust particles reduces respiration, which reduces gas exchange, photosynthesis rate, and other essential activities, finally closing the pores of tree leaves due to dust. It dries and destroys them (Lavergne and Mouquet 2015).

With the drying of trees, the frequency and severity of pests and diseases, such as the prevalence of insects, invasive species, and storms, increase, which causes leaves to fall and eventually the death of trees. These risks, which have increased due to climate change, can reduce forest productivity and change species' distribution. In some cases, the forest can resist these disorders and recover if they occur. In other cases, existing species may change their ecological range and create new types of vegetation. This risk is significant in rare and endangered species.

7.1.2 Climate Change and Forest Fires

Fire is an ecological process that is sometimes necessary for forest ecosystems. Climate change has had a significant relationship with fires. From this point of view, it is required to monitor, identify, and evaluate climate change trends to determine the climatic conditions and how their changes are related to the rate of fires and their location. While there have been severe fires in recent years, forecasts indicate that this trend will continue and intensify in the twenty-first century. Temperature and rainfall forecasts for the twenty-first century, which will be affected by global warming and climate change, predict the possibility of fires in most parts of the world (Ramezani et al. 2018).

7.2 *The Impact of Climate Change on the Ecosystem of Arid and Semi-arid Regions*

The arid and semi-arid regions' ecosystems are incredibly fragile and can be easily damaged, and their development occurs under very acute exothermic conditions. Their recovery is slow, with the elimination of adverse conditions, and in severe cases, acute biological imbalance causes irreversible degradation and loss of biological power. The vulnerability of these areas' ecosystem is due to soil moisture loss, the sun's intensity, high temperatures, high drought, the weak layer of humus, salinity, water-wind erosion etc.

7.2.1 Effects of Temperature Rise on Ecosystems in Arid and Semi-arid Regions

Climate change and warming are leading to hydrological changes in arid regions due to decreasing average annual rainfall. With the change of rainfall regime, the share of floods increases. Further, by reducing the percentage of snow at high altitudes, which is one of the crucial water sources in arid areas, ecosystems of these areas lead to destruction.

Climate change also causes pests to overflow and become resistant. It reduces ecosystem productivity and increases environmental pressures. As a result, it disrupts energy flow, changes in food networks and the composition of competitions, changes in chemical cycles, loss of sensitive species, impaired stability, and the collapse of all parts of the ecosystem structure. Hydrological changes also lead to ecological imbalance, intensification of erosion, irreversible degradation, reduced biological production, and regression of vegetation and soil. Other consequences of climate change on arid and semi-arid regions' ecosystem are the extinction of vital species and genetic diversity reduction. At least 140 species of plants and animals are destroyed every day on earth (Mosayebi 2017) due to these issues.

Changes in seasons, climate violence and an increase in the number of tornadoes and hurricanes due to rising temperatures, rising sea levels, and submerged coastal beaches are due to rainfall and vegetation changes. Besides, there is some result of climate change, which include:

1. Changes in agricultural patterns,
2. Scarcity of water resources due to faster snowmelt,
3. Changes in rainfall patterns,
4. Drying up of rivers and water wells,
5. Endangering human health,
6. Changes in forests and animals,
7. Increase in albedo,
8. Increased barley dust,
9. Reduced soil moisture,
10. Reduced rainfall in areas that are already dry,

11. High need for irrigation,
12. Increased salinity,
13. Reduced yields and intensified desertification.

7.2.2 The Impact of Climate Change on Short-Nosed Swamp Crocodile

Habitat of the short-nosed swamp crocodile in Iran is affected by various atmospheric currents such as the monsoon system of the Indian subcontinent and the monsoon rains of the Indian Ocean. Accordingly, the climatic regime of the region cannot be considered simple due to its topographic situation. Significant phenomena in this area include strong winds, sandstorms, torrential rains and thunderstorms, high humidity, and morning fog. Due to the different moisture supply sources in the region, rainfall patterns in the Bahuklat River basin, the primary habitat of crocodiles, are entirely independent of other parts of Iran and even independent of the northern region of Balochistan. Rainfall in autumn and spring is in heavy showers and the infiltration of monsoon winds, followed by rains. High air temperature increases the rate of evaporation. Therefore, this region can be considered the wettest point in the country's southern and eastern parts, with a humid maritime climate in which crocodiles are well adapted. The annual increase in temperature has led to increased evaporation, exceeding water resources' capacity, and drought in recent years. Drought reduces the riverbed's water volume and reduces fish reproduction, which is the central part of the crocodile's diet. Despite many changes resulting from climate change, this valuable species of wildlife has survived well with insufficient access to food and dehydration and has changed its diet to some extent, which is a clear sign of wildlife adaptation to climate change (Pouresmaeily and Eftekhari 2017).

7.3 The Effect of Climate Change on Aquatic Ecosystems

One of the most critical ecosystems globally is the aquatic ecosystems, which help increase biodiversity and increase ecological productivity. Besides, marine ecosystems can play an essential role in drinking water supply, irrigation water, and fisheries production. However, today these ecosystems are exposed to various hazards, including human activities, climate change, and pollution; for this reason, an area of these valuable resources is destroyed annually.

One of the leading aquatic ecosystems, and the primary biodiversity, is freshwater ecosystems and coastal wetlands. These ecosystems have many benefits for civilization and human well-being, listed in Table 1. These services are provided from four different sources: rivers and streams, ponds and lakes, coastal wetlands and freshwater wetlands. However, the remarkable thing about this is the strong impact of human activities on these biological communities (Reid and Cooke 2019).

Many human activities lead to greenhouse gas production to play an essential role in global warming and climate change. Predicted climate change puts much pressure

Table 1 Classification of freshwater ecosystem benefits (Reid and Cooke 2019)

Supply of Water	• Drinking • Cooking and washing • Irrigation • Aquaculture • Manufacturing and power generation • Other industrial uses
Supply of on-water goods	• Timber products • Fish, shellfish and crayfish • Clams and mussels • waterfowls
Supply of non-extractive benefits	• Flood control • Biodiversity • Transportation • Recreational activites (boating and swimming) • Coastal protection etc

on freshwater ecosystems, which are already under pressure due to other destructive factors. Although aquatic ecosystems are highly resistant to harmful elements, climate change sometimes destroys much of them by applying double pressure.

7.3.1 Climate Change and Aquatic Environment

Climate change's ecological consequences rely on the rate and degree of change in several key environmental factors like temperature, precipitation, and water supply. These elements actively and indirectly regulate different ecological processes in the aquatic settings (Fig. 3) (Apostolaki and Samartzis 2019).

Numerous ecological techniques and models in aquatic freshwater and coastal wetland habitats are regulated by the connection between high carbon dioxide and temperature and precipitation factors. Temperature directly influences certain important life processes. Variations in the thermal regime (e.g. high temperatures, length, and seasonal temperature change rates) may substantially impact species growth and generation rates since each aquatic and wetland species is evolved to a specific temperature range. Global warming will push species' projected regional ranges north or higher in mountainous places. Additionally, the southern (or lower) section of certain species' geographic ranges would become unfit. The capacity of species to extend their ranges depends on the number of resources and the ability of species to travel along dispersion corridors, which vary by type of aquatic Environment (Apostolaki and Samartzis 2019).

The water volume in an aquatic ecosystem significantly influences biological systems by analyzing the quantity available and habitat consistency. Locally, precipitation and drainage patterns dictate how water volume in marine habitats transfers through time. Seasonal water depth change similarly affects the kinds of organisms

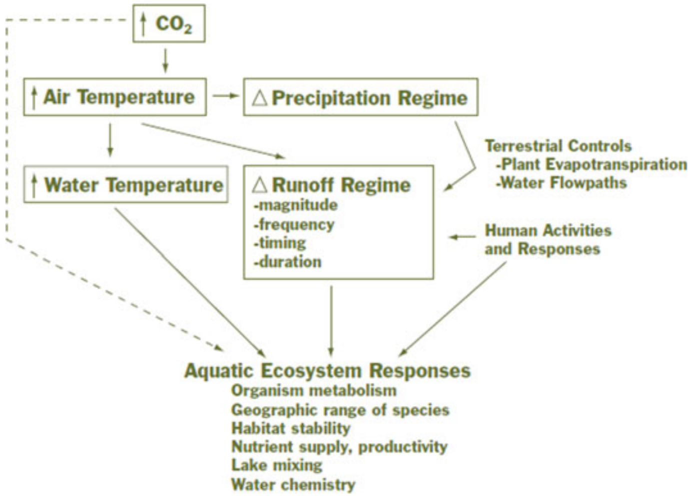

Fig. 3 Correlation between increased carbon dioxide and environmental drivers of temperature and precipitation (Solid arrows show direct responses; dashed arrow indicates direct effects of lesser-known importance)

that can survive in an aquatic habitat. Thus, a shift in the regional Environment that disrupts the present hydrological system can substantially modify habitat appropriateness for a range of species, resulting in severe ecological changes (Apostolaki and Samartzis 2019).

7.3.2 Aquatic Ecosystems' Responses to Climate Change

A. Rivers and Streams

Stream and river ecosystems consist of two components: the aquatic Environment and the adjacent floodplain or riparian area. Climate change's expected impact on these ecosystems depends on how thermal and streamflow regimes differ from current levels. Regional and local contexts would govern the degree of variance.

Change in temperate

Rising air temperature resulting from global warming will lead directly to increasing water levels in most lakes and rivers, changing essential ecological processes and species densities. Streams and canals are shallow, unstable and well-mixed systems, meaning they transfer heat and oxygen fast with the surrounding environment. They become colder due to expected climate change, e.g., a 4 °C rise in water temperatures in current habitats would result in a 680-km northward shift in thermal regimes (422 miles) that would adversely affect aquatic ecosystems (Apostolaki and Samartzis 2019).

Many aquatic creatures have temperature-dependent lifestyles. Higher water temperature has been demonstrated to boost growth rates and habitat production. For example, web-based marine invertebrates (e.g. aquatic insects) may mature faster and reproduce more frequently. If food resources stay constant, the productivity of invertebrates in streams and rivers may improve, resulting in different fish food. Nonetheless, greater water temperatures can increase microbial activity and degrade organic matter quality, resulting in lower invertebrate and fish food. Additionally, warmer water has less oxygen dissolved, reducing water consistency for organisms like invertebrates and fish that need a lot of oxygen.

B. Lakes

Historical data reveal that lake distribution in prior climate change eras varied substantially when the balance between precipitation, evapotranspiration, and runoff varied. Numerous physical and chemical features of lake ecology are governed by the lake's temperature, the amount of heat it receives from and provides to the atmosphere, the quantity of nitrogen given by the watershed, and the lake's water retention time. Together, these factors influence the lake's thermal characteristics and dissolved oxygen supply, altering habitat appropriateness.

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Climate Change and Concurrency of Extreme Events

Ehsan Modiri

Abstract This study investigates the Spatio-temporal multivariate analysis of extreme flood events, overcoming some univariate analysis disadvantages. So far, a vast range of techniques has been expanded and applied in hydrology to perform univariate analysis of extreme events. Nevertheless, univariate statistics cannot discover the flood spatial interactions within catchments. Also, the multivariate analysis of such variables is less performed in this issue because the few applicable numbers of multivariate models are not suited to represent extreme values that co-occurred. Due to the constraints of some traditional multivariate techniques regarding the handling of the dependence structure, limited approaches are appropriate when the extreme values are likely to co-occur. This chapter investigates the behaviour of the coincidence occurrence of flood events in both temporal and spatial resolution. One of the main concerns of this chapter is gaining more knowledge about the synchronous flood occurrence in upstream sub-basins that can contribute to flooding risk management due to different spatio-temporal precipitation distributions outflows in these sub-basins. Moreover, the performance of simultaneous clustering events is illustrated based on some appropriate and newly proposed clustering methods. This chapter also explains the ideas behind the high dimensional clustering in concurrency of floods.

Keywords Floods · Risk management · Clustering · Multivariate analysis · Floods concurrency · Flood protection

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1 Introduction

1.1 Climate Change and Global Warming

Climate change is an alteration in weather patterns occurring over longer scales and related changes in oceans, ice sheets, and land surfaces. From shifting weather patterns that threaten agricultural production to ice sheet melting and consequent catastrophic flooding, climate change impacts are global in scope and unprecedented in scale (United Nations 2020). Climate change indicates that many natural ans anthropogenic forces contribute to global warming around the world (Philander and Philander 2008). However, human activities are estimated to have caused around 1.0 °C rise in global warming above pre-industrial levels, with a presumable range of 0.8–1.2 °C. Consequently, global warming is expected to gain 1.5 °C from 2030 to 2052 if it continues to increase at the current rate (Masson-Delmotte et al. 2018). Global warming is generally expected to vary the magnitude and frequency of extreme precipitation events, leading to frequent and more intense flooding (Dankers and Feyen 2008). However, in some research, a connection between greenhouse warming and weather extremes was not confidently expressed (Francis and Hengeveld 1998; Kundzewicz et al. 2014).

In the current study, the Neckar catchment in the southwest of Germany was chosen to investigate. This catchment is a tributary of the Rhine river, with an area of around 14,000 km^2. Figure 1 gives a precise overview of the global warming effects during the last 55 years on the Neckar catchment in Germany.

As Fig. 1a shows, the positive orientation is vivid since 1961 in the Neckar catchment. The least-squares line and the Theil-Sens slope show almost 1.9 °C temperature rise in this region, which is higher than the estimated 1.5 °C temperature enhancement (Masson-Delmotte et al. 2018). Also, Fig. 1b indicates that in addition to a positive trend in temperature time series, in 1989, the time series is divided into two parts. This abrupt change is a clear warning sign in this region. The atmosphere's saturation vapour pressure increases with temperature; a warmer climate will result in higher atmospheric moisture content and global mean precipitation. While the troposphere's energy budget constrains changes in the mean precipitation, the intensity of extreme rainfall events is relatively constrained by moisture availability in the atmosphere (Dankers and Feyen 2008). It seems that the hydrological cycle components impact each other. Increasing/decreasing one hydrometeorological variable will affect other parameters in the nexus of atmosphere and biosphere, such as global warming impacts on flood risk (Lorenzo Alfieri et al. 2017, 2018; Allamano et al. 2009; Bubeck et al. 2019; Schiermeier 2011). However, the earth tries to make a balance for a million years (Kureethadam 2014).

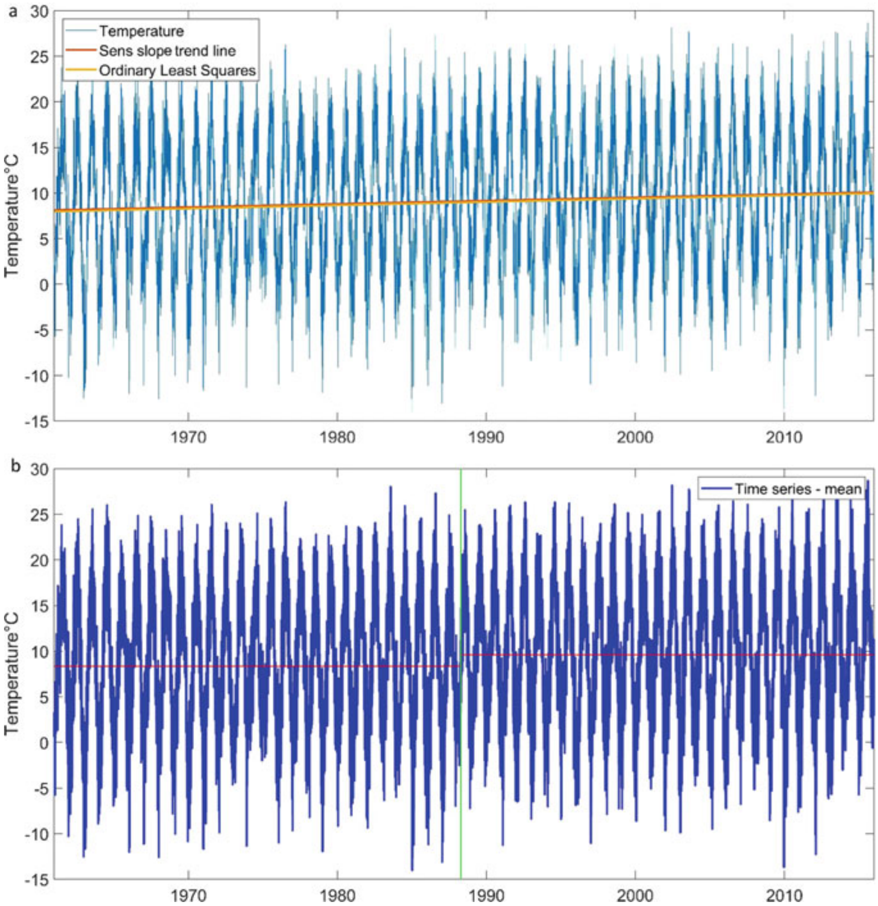

Fig. 1 **a** Temperature time series in the outlet of the Neckar catchment, Theil-Sens slope = 0.0356°/year, ordinary least squares = 0.0363°/year, **b** detected abrupt change point in 1989 in temperature time series

1.2 Extreme Events: Floods

Floods are among the significant climate-based disasters. In the past decades, reported annual flood losses have reached tens of billions of dollars, and thousands of people have been affected each year. These extreme events have led to more than 426 billion euros of losses in Europe between 1980 and 2017 (European Environment Agency 2019). The maximum estimated annual damage of river floods in China was recorded in 2010, with a total loss of 51 billion US dollars (World Bank Group 2020). Pakistan's monsoon floods in 2010 killed nearly 2,000 people (Syvitski and Brakenridge 2013). There are plausible physical mechanisms by which global warming could alter both the intensity and frequency of some kinds of extreme weather events.

Also, changes in extreme weather events will be irregular, and the detection of trends will be complicated (Francis and Hengeveld 1998). Climate change can substantially change human exposure to the flood hazards by increasing the vulnerability zones (Modiri and Modiri 2016). Also, changes in the magnitude and return period of floods is mentioned in some research (Alfieri et al. 2015; Bertola et al. 2020; Burn and Whitfield 2016; Dankers and Feyen 2008; Milly et al. 2002; Modarres et al. 2016; Monirul Qader Mirza 2002; Petrow and Merz 2009). However, there are considerable uncertainties in the power of this impact between different projections of regional change in climate (Arnell and Gosling 2016). Furthermore, direct factors responsible for changes in flood severity and magnitude could result from climate change, but watershed surface changes and river engineering can also play a role (Kundzewicz et al. 2013). Therefore, climate change and urbanization can have significant combined effects on flood damage and optimal long-term flood management (Zhu et al. 2007).

Floods in different parts of the world during 2010–2011 demonstrated all countries with a distinct level of income struggle to cope with extreme weather events (Wilby and Keenan 2012). Although the total direct costs of disasters may be most extraordinary for high Gross Domestic Product (GDP) countries, the economic impact is more extensive for middle-income countries because of their rapidly expanding asset bases (Sanghi et al. 2010). Therefore, it does not matter where humans live; the floods' socio-economic losses are inevitable and have significantly increased, mainly driven by the expanding exposure of assets at risk (Kundzewicz et al. 2014). Another issue in flood analysis could be the fact of overpopulation. Since decades ago, the population has increased in most flood-prone regions, enhancing these areas' risk (Bouwer 2011, 2013). Therefore, changes in population, development, and protection level strongly influence flood hazards exposure (Brakenridge et al. 2013).

2 Concurrency of Extreme Flood Events

Floods that simultaneously affect many sites might be a dispute with flood disaster management systematization. In terms of the definition of concurrency of floods, simultaneous floods occur in different parts of a region (Diederen et al. 2019; Modiri 2021). So far, the mapping projects have not taken the simultaneous occurrences of extremes into account, which play a significant role for planers in flood risk management, flood generating mechanisms, and the triggering system (de Moel et al. 2009).

The investigation of the simultaneous occurrences of flood events is one of the newest challenges in hydrology. The two definitions of "maximum possible flood" and "maximum probable flood" were defined based on consideration of the chances of simultaneous occurrence of the maximum adverse conditions (Bertle 1973; United Nations 1964). Due to synchronizing flood events on the Rhine, Main, and Neckar rivers in Germany in the last two decades, enormous loss near the urban regions took place (Kron et al. 2019; McPhillips et al. 2018). After the flood in 1995 in the Meuse river in the Netherlands, the government decided to evacuate around two hundred thousand people living in the floodplain areas (Geertsema et al. 2018). These experiences showed massive socio-economic impacts on this region. The flood hazard increased significantly when floods arrived simultaneously in the Brahmaputra rivers. The high-intensity floods in Bangladesh occurred when any two of the three major rivers reached peak flow conditions simultaneously (Monirul Qader Mirza 2003; Monirul Qader Mirza 2002). Analysis of the data showed that the frequency of simultaneous flooding in all the rivers in Georgia is 15–20 years (Tsivtsivadze et al. 2019). Therefore, the depth and extent of floods and associated damages are extensive when the major rivers simultaneously reach their peaks.

One of the aspects that may lead some regions to have simultaneous flood occurrence is urbanization in a large city or land-use change. Significant floods in cities can trigger simultaneous flooding by river water and inland flooding (Koyama and Yamada 2020). However, river flooding may be concurrent with storm surge or extreme tide events (Brakenridge et al. 2013). Yinkang (1996) also mentioned that the floods in the Huaihe river basin in China have simultaneous and successive occurrence. Newton (1983), indicated that the coincidental events of floods are significant in designing high-hazard dams or power plants to keep the risk of failure to zero. Therefore, it is required to investigate the behaviour of concurrent floods in a catchment or a region.

The proposed research aims to investigate the coincident occurrence of flood events to understand to what extent floods react together in time and space. Moreover, the appropriateness of clustering methods in multivariate analysis, especially simultaneous occurrences of floods is also shown.

2.1 Challenges in the Flood Concurrency Analysis

There are two major challenges in simultaneous grouping occurrences of flood events. The first one is to what extent these floods happen in space and how they react simultaneously. The second challenge is: what kind of clustering can handle this problem. In total, the clustering itself is a big question for hydrologists in multidimensional issues. Besides, the flood event identification is also one of the main criteria in flood analysis.

2.1.1 Flood Events Identification

Depending on the chosen method for identifying floods such as Peak Over Threshold (POT), the annual maxima, or selecting one to five independent peaks per year, some assumptions will be considered. It means each method of peak identification has its constraints. For example, POT assumes a threshold that can be different in each area or even each hydrological application. The annual maxima cannot cover the total number of costly floods due to the short length of time series, and measurements. The method of selecting some independent peaks per year covers the problem of annual maxima, but it still has an assumption to define the independence of two events. Implementing any assumptions makes the problem simpler and generates some uncertainties.

In this chapter, all the clustering results are based on the ranked correlation matrix of the flood data sets using two independent peaks per year. Therefore, the applied clustering methods work with the correlation of the data. The pairwise correlations and a sample of mapping this association in the Neckar catchment is illustrated in Fig. 2.

In Fig. 2a, the reference discharge flow is highlighted in dark red. All the related sub-catchments which have a strong correlation are shown in light red. The right part of the catchment relatively has a high correlation with each other. Figure 2b shows all correlations among flood series, but it is impossible to see a tangible map with grouped areas without clustering. Therefore, once again, it has been proven that clustering methods are needed to provide a map that shows the temporal and spatial relationships among simultaneous floods.

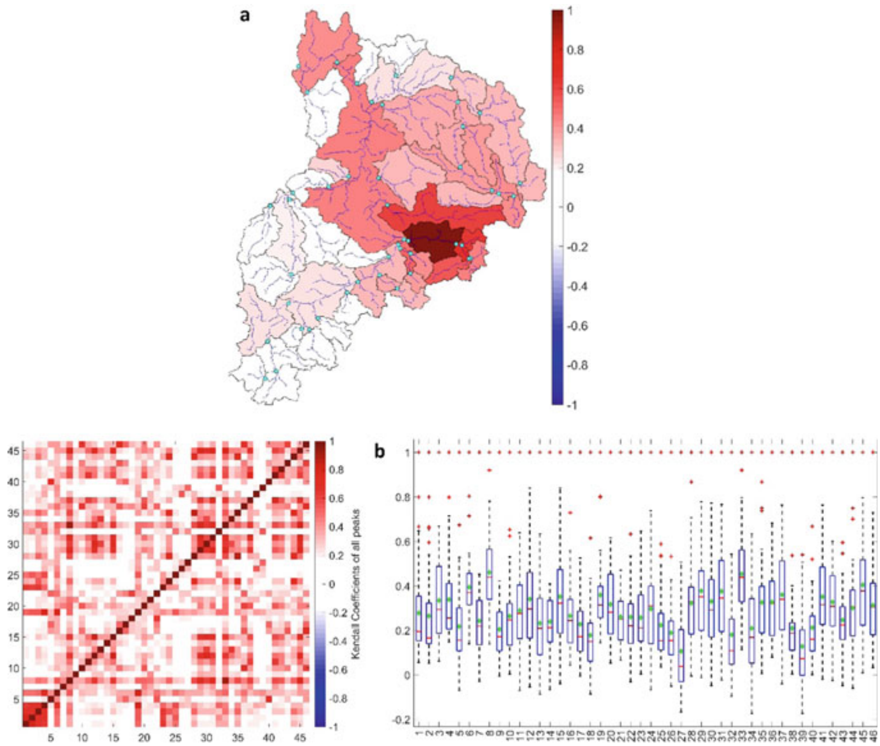

Fig. 2 The correlation of simultaneous occurrence of the most significant floods, **a** regarding the reference stations in dark red, **b** box plot and range of pairwise association among gauges

3 Clustering

Cluster analysis, groups events or observations as objects based on the information found in the data describing the objects or their relationships. The goal is that the objects in a group should be similar to another and different from the objects in other groups. The greater the similarity within a group and the greater the difference between different groups, the better the clustering quality can be achieved (Steinbach et al. 2004). One of the vital goals of cluster analysis is a better understanding of the data. Clustering describes the data structure in an unsupervised machine learning manner (Kriegel et al. 2009). One of the main cluster analysis applications is to evaluate exposure levels and vulnerability zones (Modiri and Modiri 2016). The high dimensional clustering can demonstrate not only floods relationship in time and space, but also their association can be visible when their magnitudes are clustered. The resulting cluster in simultaneous flood events can provide risk maps and flood protection plans, which are appropriate tools for policymakers and planners in such distinct levels of society relatively urban, rural, or landscape planers.

3.1 Challenges in Clustering

High-dimensional data pose specific challenges to clustering in hydrology. The volume of computations is increased by increasing the number of dimensions and rendering traditional clustering algorithms ineffective (Assent 2012). Most clustering algorithms require user-supplied parameters, such as the desired number of clusters or a minimum cluster size (Chaimontree et al. 2010). The majority of clustering methods have been designed for 2D space, such as the traditional k-means or density-based and spectral clustering. Therefore, finding a convenient clustering method to work in multivariate analysis is a highlighted point. Each method has specific goals and subsequently has advantages and disadvantages regarding the concept of the application. Despite the high accuracy of a particular method, it should not be selected for clustering, if it is time-consuming.

The first thing in hydrometeorological clustering might be having a standardized data set in terms of neglecting the effect of the size of the catchment or the variable magnitudes. For example, naturally, the outlet of a catchment takes more flow in comparison to upstream sub-catchments. Therefore, standardizing the input data is an appropriate way to prevent some errors. In this chapter, we have tried to prevent writing any mathematical equations so that the reader does not deviate from the research path.

3.2 AHCT Clustering

In high dimensional approaches in hydrology, the Agglomerative Hierarchical Cluster Tree (AHCT) method that does not depend on the predefined number of clusters or any other assumptions is used. It works with a wide range of distance metrics and is broadly applied in clustering schemes. This grouping variable needs to have a distance matrix or dissimilarity matrix as an input and can handle both raw data vectors and correlation matrix of the data (Modiri and Bárdossy 2018).

Although pairwise investigations cannot detect higher-order dependencies, they may be applicable to be used as an input in clustering in some cases. Hierarchical clustering utilizes the pairwise analysis and constructs the linkage tree based on the space between two clusters. Hence, (Davidson and Ravi 2005) presented an agglomerative hierarchical clustering by some constraints, which improve clustering. Agglomerative constructs hierarchy in the opposite direction, which makes different results. This method begins when all objects are away from each other, then two clusters are merged in each level. It continues until only one remaining object (Sarle et al. 1991).

The number of clusters can be reached in the dendrogram and verified by different clustering methods. In general, there are five essential linkage algorithms, including single, complete, average, weighted, and Ward, that each of which follows a term of distance (Kaufman and Rousseeuw 2009). For example, the single linkage uses the smallest distance between objects in two clusters and tries to find the nearest neighbour. This method's main advantage is to be flexible in high dimensional space and does not need to have any assumptions about the number of clusters or threshold. However, it is possible to set different limitations for this kind of clustering. The input can also be an initial series of data, correlation, similarity matrix, or any sort of distance matrix.

Here, in this case (Fig. 3), the dendrogram shows three main clear clusters; however, in the polar dendrogram let us select four clusters by splitting the dark blue group into two separate clusters. Therefore, choosing an appropriate linkage method is critical, but some post hoc tests can find the best possible clustering, which has to be considered (Modiri and Bárdossy 2021).

3.3 PCA—AHCT Clustering

Principal Component Analysis (PCA) is a mature technique that allows constructing a broad range of similarity measures to grasp the local correlation of attributes and to find arbitrarily oriented subspace clusters (Kriegel et al. 2009). It is a well-known dimension reduction technique defined as an orthogonal-linear transformation that transforms the data into a new coordinate system (Jolliffe 2002). Usually, in discharge flow time series, the first principal component (PC) explains the high percentage of data variances. In Fig. 4a, the first three PCs explain more than 85% of this research

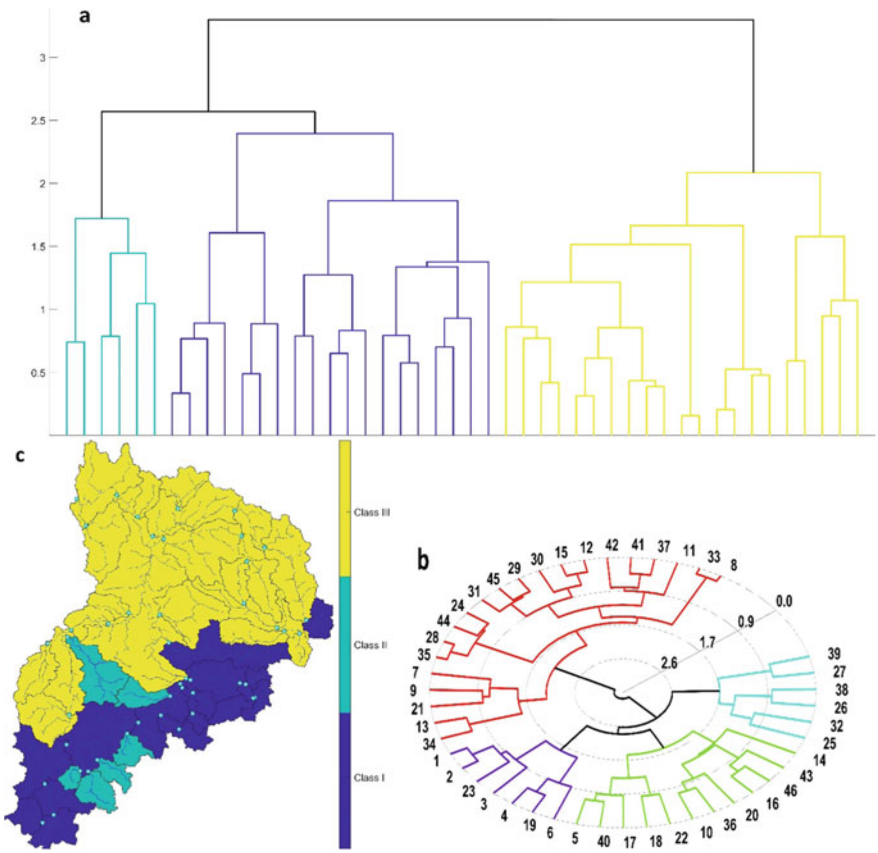

Fig. 3 Agglomerative hierarchical cluster tree, **a** dendrogram form, **b** polar dendrogram form, and **c** mapping AHCT clustering of simultaneous occurrence of floods in the Neckar basin

area's variance. In this method, the first PCs or corresponding reconstructed series will not be directly usable as an input of clustering (Modiri and Bárdossy 2019). This method's main idea is reconstructing the whole time series based on the first PCs of the high dimensional data by employing Singular Value Decomposition (SVD). Then, to remove the impact of seasonal cycles, the two original and reconstructed time series have to be subtracted. The residual or pure data series will identify flood events and subsequently find dissimilarity matrix out of new flood series.

The PCA-based procedure of generating residual time series neglects some periodic seasonal terms like an annual and semi-annual cycle and other powerful seasonal signals in the first PCs and catches the main behavior of the whole dataset. The residual time series almost does not have these terms, although the peaks' indices are still the same as the original time series. However, the residual time series's magnitude is smaller than the original one, which is what the method wants. Therefore, if someone deals with the seasonal components in hydrology, the PCA-AHCT

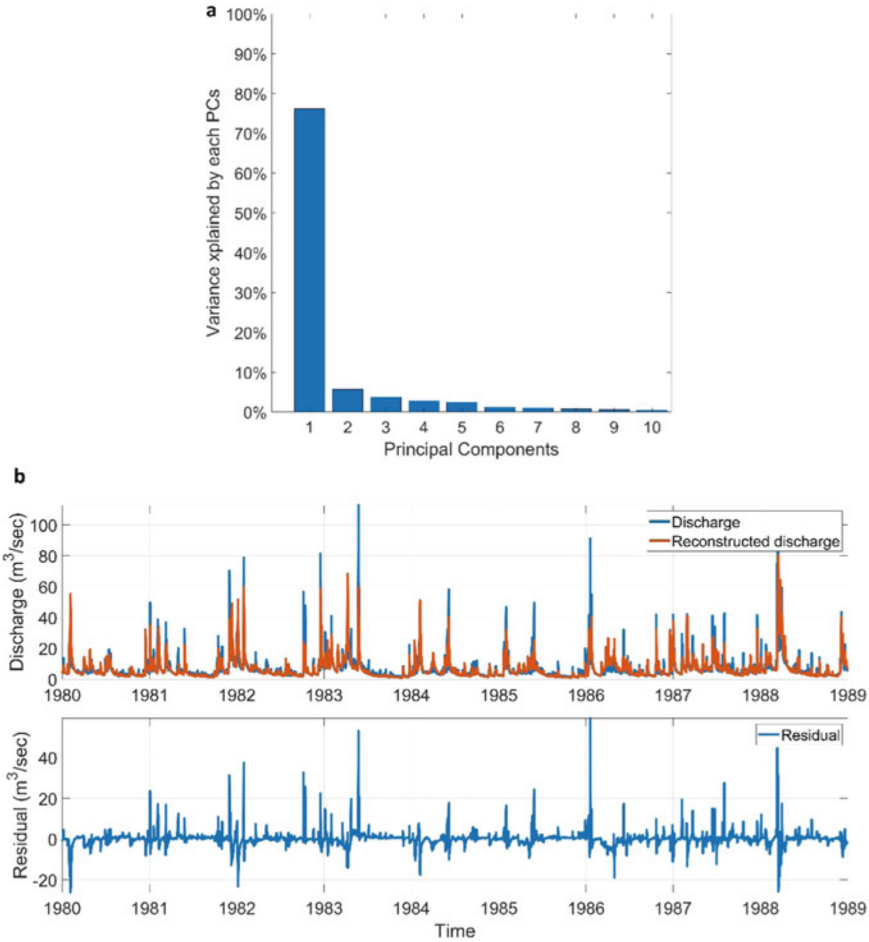

Fig. 4 Principal component analysis, **a** explained variances by each PCs, **b** reconstructed discharge time series based on first three PCs and the residual time series of simultaneous occurrence of floods in the Neckar basin (Modiri and Bárdossy 2019)

method can be used for clustering. This method has the disadvantages of demanding a threshold to select the first PCs as a level of the variance explained, and neglecting the non-linearity effects between variables due to its linear transformation nature.

3.4 Multidimensional Scale Clustering (Classical MDS)

Multidimensional scaling (MDS) is a visual representation of distances or dissimilarities between sets of objects, and the objects in this chapter are the discharge measurement across the Neckar catchment. However, they can be colors, faces, map coordinates, political persuasion (Kruskal and Wish 1978). More similar objects are closer together on the graph than less similar objects, similar to the clustering scheme's goal. The major highlight of this method is interpreting dissimilarities as distances on a graph. Also, MDS is divided into two parts, including classical and non-classical. In this study, the classical multidimensional scaling is applied. It can also serve as a dimension reduction technique for high-dimensional data (Buja et al. 2008). Although MDS has some similarities with the PCA method, it is not the same in concept and mathematical equations. These two methods are identical if only the first two PCs will be captured and taken into consideration.

MDS is utilized over a wide variety of disciplines. Indeed, any matrix can be analyzed with this technique as long as the matrix contains some relational data such as correlations, distances, multiple rating scales, or similarities (Cox and Cox 2008).

Figure 5 shows the two-dimensional graph of MDS for concurrent floods in the Neckar catchment. As is clear by randomly dividing the figure into four equal quarters, some data groups are recognizable. Despite its simplicity, this method has weaknesses, including data grouping that requires implementing other hypotheses

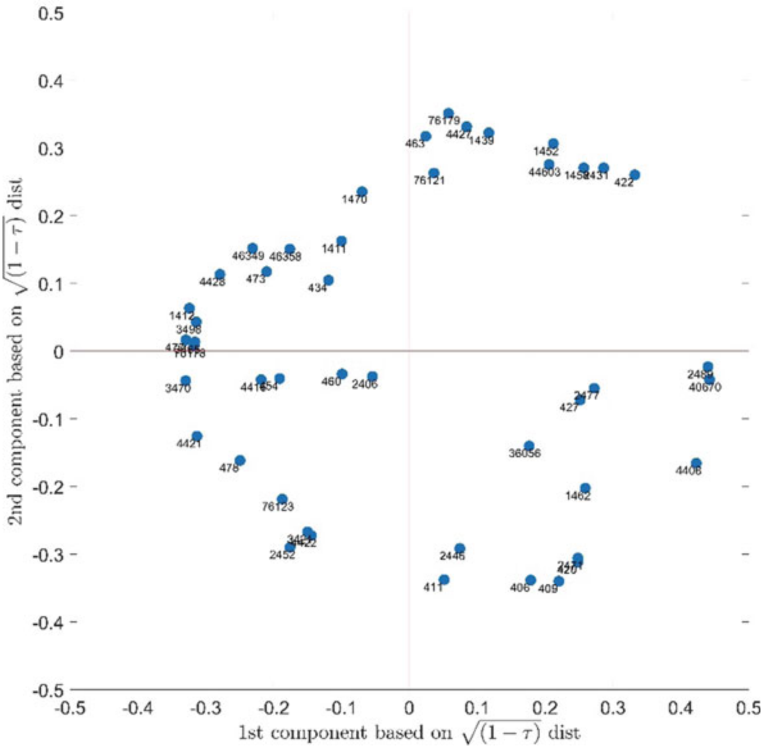

Fig. 5 Multidimensional scaling on the simultaneous flood in the Neckar catchment and Kendall similarity matrix

and models. Also, the problems of the PCA method are repeated here. Further, in comparison to the AHCT method, MDS has to have a symmetric and square matrix to work, while AHCT can be run with all asymmetric matrices. One of the positive points of this method is the simplicity of implementation and the association between different flood magnitudes in measuring stations.

3.5 MDS—K-Means Clustering

This method is a manipulation between the famous k-means clustering and multi-dimensional scaling. These two methods alone cannot solve the problem of high dimensional data. As mentioned in the previous part, the MDS itself needs to have another way to cluster data into 2D space. Also, k-means is traditionally defined in two dimensions (Lloyd 1982) and the combination of these two methods can solve the mentioned problem.

Figure 6b shows the application of the k-means on MDS. The k-means can be run for each pair of measurement gauges. The MDS-k-means method solved the above-mentioned clustering problem. However, due to dimension reduction, the challenge remains, i.e., what this research wanted? Does it cover all of the issues? The simple answer is no; it needs to consider the non-linearity and not be sensitive to the object matrix's asymmetry.

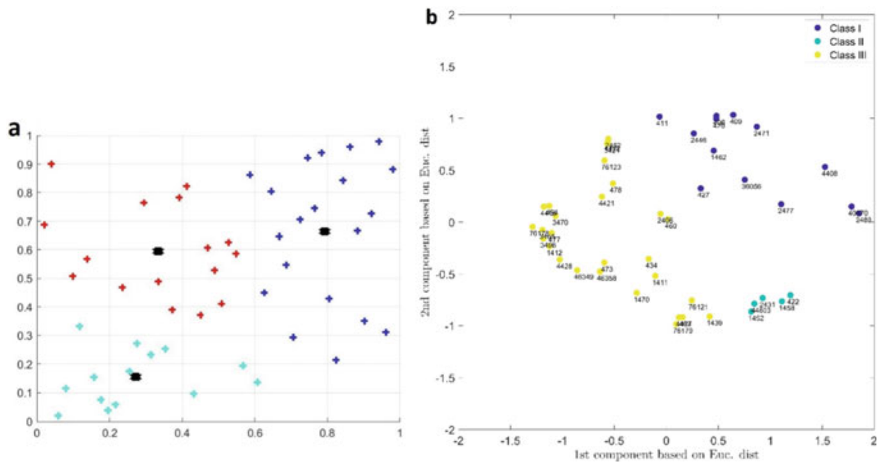

Fig. 6 **a** k-means clustering of the floods in two different part of the catchment **b** Multidimensional scaling—k-means on the simultaneous flood in the Neckar catchment

3.6 *t-SNE Clustering*

t-distributed stochastic neighbour embedding (t-SNE) is a machine learning unsupervised technique for visualization developed by Hinton and Roweis (2002) to obtain the t distribution variant (Maaten and Hinton 2008). It is almost a new nonlinear dimensionality reduction technique that is well-suited for embedding high-dimensional data for visualization in a low-dimensional space of two to three dimensions.

Figure 7 shows the scatter distribution of each gauge. Compared to the MDS method, both methods are reacting similarly to demanding an additional algorithm to cluster this 2d space. Due to the use of t-distribution inside t-SNE, this method has heavier tails. The t-student distributions have a greater chance for extreme values than normal distributions, hence the fatter tails. Therefore, if we are working with extreme events, the t-SNE clustering can be a way to cluster data in a high dimensional space. However, this algorithm has to be run in different climates and has to deal with distinct hydrometeorological variables.

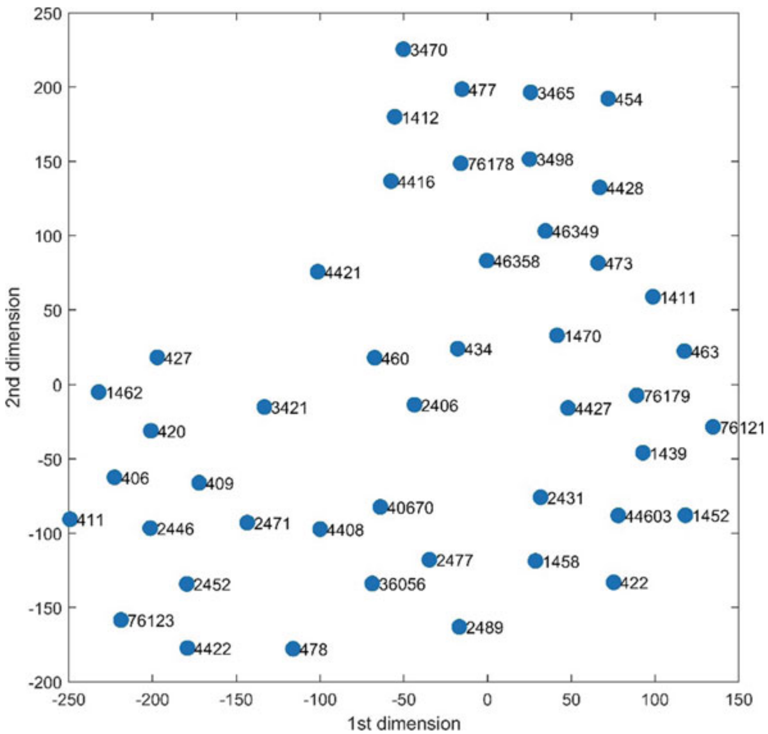

Fig. 7 t-SNE clustering on the simultaneous flood in the Neckar catchment

3.7 Distribution Based Clustering

According to the high clustering flexibility of the AHCT algorithm in the high dimensional space, the other idea to cluster flood magnitudes is to investigate their distribution and evaluate the similarity among Cumulative Distribution Functions (CDFs) of the flood series. It means, with the two-sample Kolmogorov–Smirnov (KS) test, the dissimilarity of pair distribution can be computed as an acceptance/rejection, probability, and the statistics of the test (Modiri and Bárdossy 2020b). Therefore, this method is the same as the first-mentioned hierarchical method with a distinct input. CDF of a flood series shows an empirical behaviour of events in a catchment. The similarity of two CDF's can indicate the concurrency of floods in terms of their magnitudes (Fig. 8).

The KS statistics are the maximum absolute difference between the two data vectors (Massey 1951). By implementing AHCT on the KS statistics matrix, the clustered CDFs, as illustrated in Fig. 8, show that the considerable difference between clusters, especially between 0.65 and 0.95, is a good sign for verification of resulted clusters. This method, same as others, has its own disadvantages. The KS statistics might be a necessary factor for distribution-based clustering analysis, but is it sufficient? The negative point of this coefficient is, it is only a maximum value among the whole CDF. i.e., it is possible to have a high difference between CDFs, but other parts of them act similarly. Therefore, distribution based AHCT clustering can be a good option if the research questions concerning the similarity of empirical CDF.

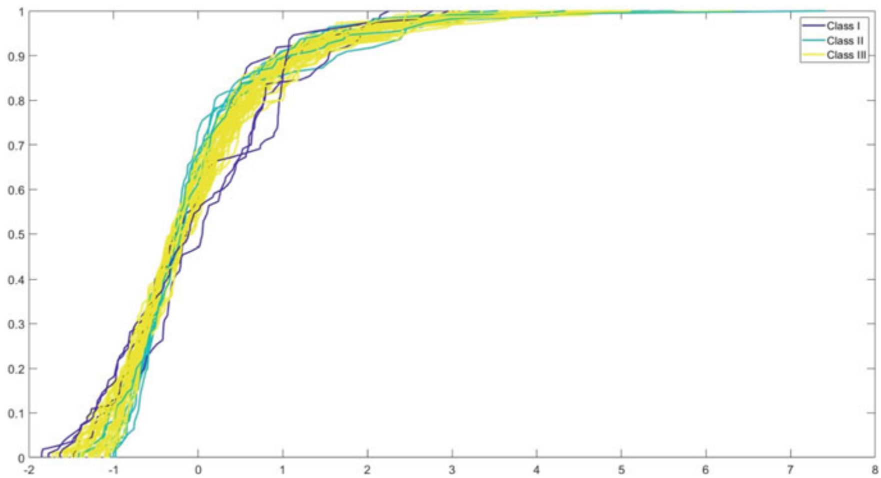

Fig. 8 The clustered CDFs of simultaneous occurrences of floods in 46 sub-catchment of the Neckar

3.8 *Optimization Scheme Clustering*

Optimization scheme clustering is a new sort of clustering to prevent having any assumptions. This method is needed to have a dissimilarity matrix as an input. The two-sample Kolmogorov–Smirnov statistics generates the model input. The Robust Simulated Annealing (RSA) is a hybrid application of Simulated Annealing (SA) inside each other. Depending on the layers of optimization, different SA levels have to be implemented in this clustering scheme (Modiri and Bárdossy 2020a). Same as other optimization algorithms, RSA optimizes one or several objective functions that can be a cluster evaluation method such as the Silhouette score (Rousseeuw 1987), Calinski-Harabasz criterion (Caliński and Harabasz 1974), Gap statistics (Tibshirani et al. 2001), or Davies-Bouldin criterion (Davies and Bouldin 1979).

RSA is initially splits the data set (in this case, flood series in 46 sub-catchments) into a random integer number (as the number of clusters). Then, randomly distributes flood series to each cluster. Inside RSA, SA starts to iterate and randomly shift one member with another member in other clusters (see Fig. 9a). At each time, an objective function is calculated and is compared to the previous step. This iteration is continued until finding the optimum value for the objective function. Subsequently,

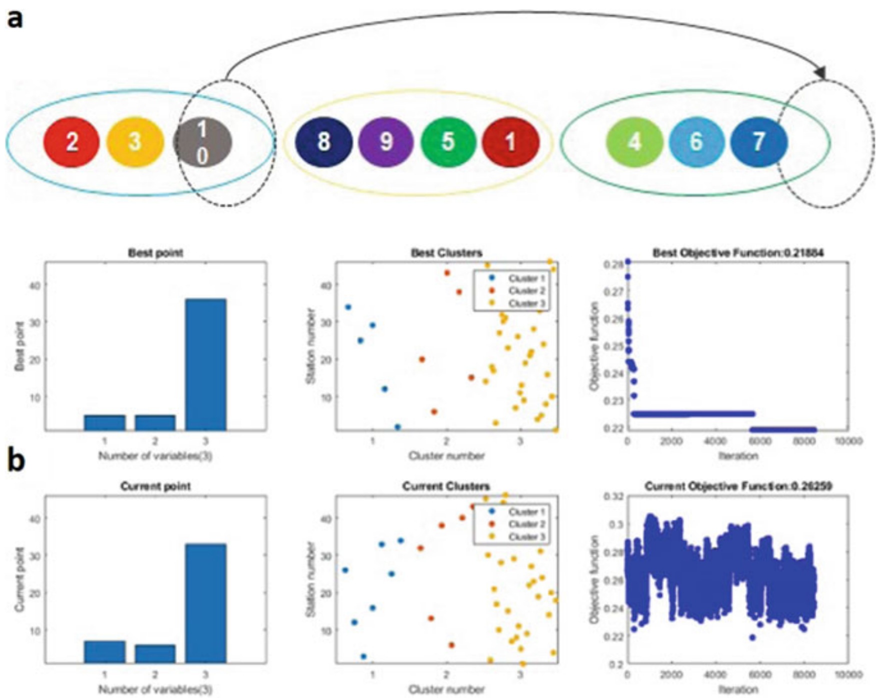

Fig. 9 Robust Simulated Annealing technique **a** the way of changing the number of members inside clusters **b** simulated annealing cooling process

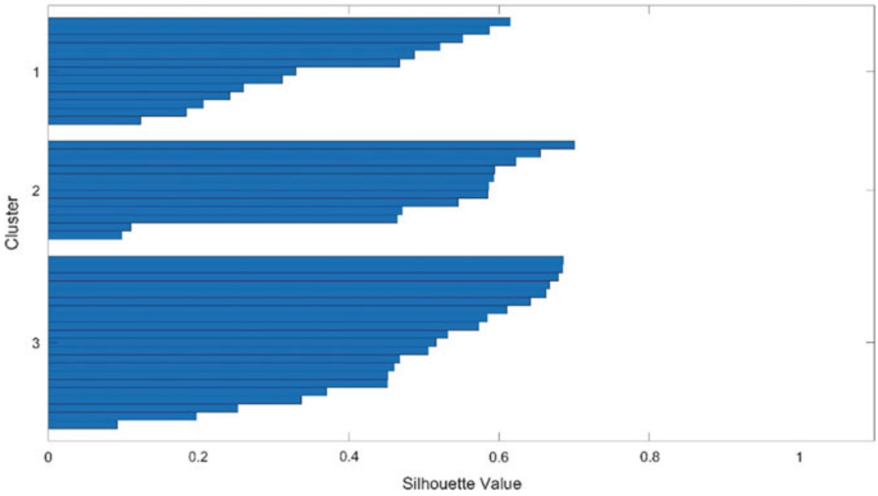

Fig. 10 The Silhouette coefficient of a clustering method

the number of members in defined clusters in the last step has to be changed and the whole procedure is to be repeated to find an optimal objective function and the number of members inside each cluster (see Fig. 9b). Depending on the layers of optimization, this scenario should recur (in this case, the number of clusters can be changed from two to six, concerning the tributaries of the main river in the catchment).

Moreover, a clustering evaluation that depends on the selected algorithm can be chosen to verify selected clustering methods. In this chapter, the Silhouette coefficient that is a score that can show the goodness of clustering is briefly explained (Rousseeuw 1987). It is one of the best cluster configuration validation techniques (Chaimontree et al. 2010) (see Fig. 10).

The Silhouette ranges between −1 and 1. Naturally, the negative or near zero scores show the wrong clustering result. The solution to revise this problem is changing the number of clusters and redo all the clustering to find the optimal Silhouette score. Figure 10 shows the performance of three calculated clusters for each observation points. The average of all Silhouette coefficients in a cluster represents the quality of clustering groups.

4 Conclusions

Here is tried to investigate the two major challenges in multivariate analysis. The first one is the spatiotemporal evaluation of simultaneous flood occurrences, and the second one is finding an appropriate clustering way for high dimensional data.

Based on the illustration of some clustering stude is in high dimensional space in extreme events, the author recommends the utilization of these hydrology methods to work with the measured data. The researchers must take care of choosing the clustering method concerning the defined problem. The resulting clusters have to be meaningful in hydrological aspects. i.e., each cluster must show some geophysical, morphological, and geological features.

It is not easy to realize the best possible clustering algorithm in hydrological aspects, and sometimes, selecting the wrong decision is worthless and time-consuming. In the end, the clustering result might be identical or relatively same as another method. The crucial point to choose a method is inside the research question and related problems. Indeed, there is no exact solution for concurrent flood analysis in high-dimensional spaces. Many techniques push the boundaries on the number of dimensions that can be handled. But, challenges remain, and still, some of them demand to have specific assumptions, which do not agree with the designed goal in this research. Therefore, there is still much research to do in clustering the concurrency of flood events. In total, the questions will often remain unclear whether solutions tackle the same problem or not. It means that it depends on the issues; the clustering method must be chosen to have some physical meaning in hydrology. The appropriate choice of a clustering approach proper to the problem should be based on information about the basic principles on which the particular clustering approach is grounded. Similarly, the interpretation of clustering results should be guided by knowing the kinds of patterns a specific algorithm can or cannot find.

This chapter tries to briefly explain the ideas behind the high dimensional clustering in concurrency of the floods. If you would like to have more detailed information, please find the author's publications. Therefore, no additional explanation has been written regarding the implemented methods in this book. This chapter is a general overview of the following challenges in clustering concurrent flood events in the basin-scale analysis; however, the proposed methods may be applied in other scales.

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Land–Coast–Deep-Sea: Restoration of Australia's Great Barrier Reef in the Era of Mass Ecological Collapse

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Abstract The rate at which anthropogenic disturbances and climate change are impacting large earth systems, like the Great Barrier Reef, a 2300 km contiguous ecological system is surpassing its regenerative capacity with up to half of its coral reefs succumbed to death. Yet, while coral regeneration campaigns are promoted by government, industry, and locals, the irony lies in the continued background development of Queensland's manufactured landscapes transforming and degrading the region's earth system dynamics and ultimately plaguing the Great Barrier Reef. Therefore, the project transcends the narrative of independent coral ecology study and dives into a deeper examination of this altered ecological dynamic from unregulated coal and carbon-intensive mines (contributing to climate change and coral bleaching) to tree felling and the erasure of woodland eucalyptus forests (at a rate of 1000 rugby fields a day) in lieu of coastal industrial agriculture and associated poison runoff into the ocean. The narrative advocates for a new regenerative connection between land (reforestation of Goonyella Riverside mine for carbon sequestration), coast (coastal restoration of Haypoint Coal Terminal and rerouted network of waterflows from industrial agriculture), and deep-sea (regeneration of Molar Reef corals), while presenting opportunities for human stewardship. The selected sites are emblematic of the larger regional issues in the region. The ecological story of the Great Barrier Reef is thus remapped, as an example of a larger earth system dynamics, and seeks to draw a blueprint of restoration through planning, landscape architecture, and digital modeling strategies in an era of extreme anthropogenic pressures. It asks, how can resilience and reprogramming a natural succession of earth system dynamics be established? And what tools exist across restoration practices, digital realms, and creative design methodologies to tell this story?

Keywords Earth system dynamics · Coral reef regeneration · Manufactured landscapes · Bounce-forward resilience · Mine reforestation · Sustainable coastal agriculture · Restoration

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1 Introduction

All healthy ecological systems are in a constant state of flux, yet catastrophic shifts due to natural or anthropogenic changes can lead to a loss of resilience and the ability of a system to recover and regenerate over time (Scheffer et al. 2001). The reality is that much of our present-day development scale and intensity continues to fracture the dynamics of the earth's system while threatening its collapse.

The Great Barrier Reef (GBR), in the Coral Sea and off the Coast of Queensland, Australia, is the largest contiguous ecological system in the world, spanning 2300 km, boasting over 3000 individual reef systems, and the largest diversity of coral and fish communities (Randall et al. 2020). The ecosystem services provided by the GBR are invaluable for fish population habitats and acting as nurseries for spawning, shoreline protection from storm surges and land erosion, yield of medicinal compounds, and generating oxygen and absorbing carbon dioxide (Reef Resilience Network 2018; Deloitte Access Economics 2017).

While reef and coral ecologies are intrinsically adapted to periodic disturbances, the rate at which extreme weather patterns and anthropogenic disturbances (including climate change) are impacting the reefs is surpassing the system's ability to recuperate. Up to half of the Great Barrier Reef has succumbed to death due to mass coral bleaching from ocean warming events in 2016 (30% death) and 2017 (another 20% death) (James 2018). Historically, reef systems in the GBR were subjected to major disturbances such as disease, bleaching, and severe weather impacts every 27 years, yet this rate has accelerated to every 6 years today, while coral ecologies can take a minimum of 10 years to naturally recover (James 2018). Coral reef microhabitats maintain the internal mechanisms to respond to local heat stress after periodic extreme events; however, the increase in the frequency of thermal stress (ocean warming) threatens to disable coral's capacity to recover (Ainsworth et al. 2016; Hofman and Hughes 2017). Furthermore, a UNESCO assessment points to the likelihood of complete collapse of world heritage coral reef systems by 2100, if CO_2 levels (causing ocean warming) are not drastically reduced (2017).

Although there are widespread regional campaigns that restore coral populations on the Great Barrier Reef, the irony is that across its land and coasts, Queensland, Australia boasts some of the world's most intensive manufacturing landscapes that are the culprit to facilitating climate change and directly polluting the GBR's ocean waters. This ranges from unregulated carbon-intensive mines (including new coal mine development, a practice that is increasingly becoming outdated) to tree felling (at a rate of 1000 rugby fields a day) in lieu of coastal industrial agriculture and associated poison runoff (The Guardian 2018). Coral bleaching and ocean acidification are byproducts of increased carbon in the atmosphere and can be attributed to activities akin to Queensland intensive mining activities. Australia today boasts 50,000 abandoned mines, essentially landscape scars due to minimal regulation on mining operations and lack of regulation for mines to be filled or cleaned up after the operation. In addition, over the last decade, Queensland has been felling 314,000 ha of trees yearly, many lands of which are converted to industrial agricultural uses (The Guardian 2018).

As the world's largest coal exporter, Queensland, Australia, accounts for 35% of all coal transported to nearby Asian countries (Lynch 2020). In 2019, Queensland, Australia, exported 226 million tonnes of coal, contributing $52.5 billion to Queensland's economy (Lynch 2020). Queensland continues production as 'business-as-usual', thereby leaving the region with acres of degraded land, abandoned mines, and a myriad of environmental impacts. On the other hand, coastal industrial agriculture has altered the balance of vegetative cover, presenting a myriad of environmental problems (Yapp et al. 2001). The clearance of vegetation has caused extensive soil erosion and acidification (Yapp et al. 2001). Although the natural process of soil acidity occurs at moderate rates, estimates show that increased mining and coastal industrial agriculture will rapidly degrade soil under *annual* pasture regimes (Yapp et al. 2001). Furthermore, intensively used zones in Queensland, Australia have decreased the pH level of less than 5.5 for 60% of soils in the region (Yapp et al. 2001). Moreover, mining has introduced salinization, which can emerge years and decades after land clearing, affecting water usage for wildlife and neighboring communities. It is predicted that land affected will treble in the next 50 years (Yapp et al. 2001)—a concern that threatens our earth system dynamics. In addition, mining practices have significantly impacted groundwater resources, where artesian bores have been left to run freely, resulting in the excess of approximately 90% of the water that is extracted—all of which has been wasted (Yapp et al. 2001).

Furthermore, Queensland, Australia is home to the endangered southern Black-throated finch, a species that has lost 80% of its former habitat due to mining activities (Vanderduys and Reside 2020). In addition, temperate eucalypt woodlands have been almost completely eliminated from the landscape, with approximately 3% remaining (Yates and Hobbs 1997). Once widespread, this species has been cleared for agriculture or grazed and converted to pasture (Yates and Hobbs 1997).

Poorly regulated coastal agriculture continues to be a source of algae bloom and thorn of the starfish outbreaks (COTS) in the Great Barrier Reef Heritage area. Up to 1000 adults can invade a single hectare of the reef during an outbreak and infestation can destroy over 97% of a reef's coral population (BBC One 2015). On a similar note, the Government of Queensland, Australia has recently approved 1 million tons of sludge to be dumped in the Great Barrier Reef area, causing toxic water quality and coral choking when sediment settles on the reef. While the literature is extensive on coral marine biology and reef regeneration, the story requires representation across a more holistic scale to better understand the complexities between human agency and the earth system dynamics of the twenty-first century.

Hence, the narrative advocates for a new regenerative connection across land, coast, and deep-sea. Given the altered earth system dynamics due to anthropogenic disturbances, it asks how resilience and reprogramming of natural succession of earth system dynamics can be re-established? What tools exist across restoration practices, digital realms, and design methodologies to tell this story and reconceptualize it?

This practical research ultimately remaps the Great Barrier Reef's ecological story as an example of larger earth system dynamics and seeks to draw a blueprint of restoration through planning, landscape architecture, and digital modeling strategies in an era of extreme anthropogenic pressures. This research targets three sites along a 300 km transect: Goonyella Riverside mine (a 3 km wide coal mine where clean-up and reforestation strategies are proposed to enhance carbon sequestration and land reproductivity), Haypoint Coal Terminal (a prominent coastal coal shipping terminal surrounded by agricultural and grazing lands where a rerouted network of waterflows and coastal replanting is conceptualized), and Molar Reef (where existing and novel coral regeneration strategies are proposed). The selected sites are emblematic of the larger regional issues and a range of existing novel restoration strategies are explored to facilitate an ecologically resilient, connected, and productive landscape and ecological dynamic.

2 Literature Review: Ecological Restoration Across Earth System Dynamics

In order to re-establish a regenerative earth system dynamic across the land, coast, and deep-sea for the Great Barrier Reef, this section delves into the leading ecological restoration practices, as it specifically relates to the degradation and impacts of industrial activities in Queensland, Australia. This includes mine reforestation, regenerative agricultural and coastal land restoration, and coral reef regeneration.

2.1 Mine Restoration

The nature and extent of environmental disturbance as a direct result of mining has polluted air and drinking water, harmed wildlife and habitat, and has permanently scarred vast areas of land across Queensland, Australia Hobbs (2017). Soil acidification, weak soil structure, and limited water resources are the reasons why the landscape has continuously deteriorated over the past few decades Hobbs (2017). Ultimately, the extent of disturbance in the region has introduced new and challenging concerns that severely alter the ecology and quality of these sites. Thus, restoration propositions are required to reverse these impacts and ensure a return of a healthy ecosystem that re-establishes earth system dynamics across Queensland, Australia.

Among some of the most comprehensive guides of mine restoration is the Forestry Reclamation approach by the Appalachian Regional Reforestation Initiative (AARI) and the US Federal Government. The research and methodology were originally conceived to reforest the Appalachian forests and coal-rich lands (spanning the states of Kentucky, Tennessee, Virginia, Maryland, West Virginia, and North Carolina), where surface mines operated for more than 2.4 million acres in the region since

1977 (US Forest Services 2016). The methods demonstrate the practicalities of reforesting large swaths of degraded lands with high-quality soil, water and air quality, high productivity hardwood trees to promote high survival and growth rates, and to bring back the native wildlife to the region. These efforts are thought to counteract historically high seedling mortality, slow growth, poor land reproductivity, severe erosion, sedimentation, landslides, mass instability and to promote biodiversity beyond grasses, shrubs, and non-native species (US Forest Services 2016). The Forestry Reclamation methodology establishes a framework of five fundamental steps, including establishing a suitable rooting medium for good tree growth that is no less than 4 feet [consisting] of topsoil, weathered sandstone, or the best material; loosely graded [topsoil] to create a noncompacted growth medium; groundcover species that are compatible with growing trees; two types of trees [consisting] of early successional species for wildlife and soil stability, and commercially valuable crop trees; [and] proper tree planting techniques (US Forest Services 2016). Through these practical research approaches on the site-specific scale, this methodology was successful in creating lands where forest development was rapidly re-established in the Appalachian region and reoriented toward its natural successional path and healthy ecological system dynamic. The scale of reclaiming mined landscapes was specifically opportune for regrowing severely endangered species like the (blight-resistant) American Chestnut, which was predominant in the region.

Across the Bowen Basin in Central Queensland Australia, where coal mining is the predominant operation, there is a tendency to restore mine landscapes with self-sustaining Eucalyptus woodlands for the subtropical climate (Bell 2001). The dragline operations of coal mining create a landscape that consists of parallel ridges with saw-toothed crests that are first rectified in this approach by elevating the land and recontouring with an undulating topography of slopes less than 20% in order to control erosion and manage the water flows (Bell 2001). In addition, this approach also has the following features: overburden that is reshaped into a series of approximately 0.25-ha ponds, the creation of 1–2 m gullies at the base of draining slopes at the beginning of the revegetation phase, topsoil is used to cover all slopes, and the vegetative establishment is initiated with aerial reseeding of grasses, shrubs, and trees (Bell 2001). Annual vegetative surveys reveal the success of this approach; internally draining slopes maximize the yield of tree biomass and vegetative growth, vegetative cover leans toward a native eucalyptus mix, established trees have flowers with viable seeds for secondary colonization, and a wide variety of health indicator species have appeared including ant colonies, fungal bodies, and organic build-up (McNamara et al. 1999).

In Acland, Queensland, Australia, directly south of the Great Barrier Reef, a tertiary study demonstrates the efficacity of returning farmland turned coal mines back into land use for commercial cattle pasture growth. Bennett et. al's investigation took place over a 5-year period and compared the restoration process across abiotic land reproductivity metrics to 18 unmined lands used for cattle production in the region (2021). The restorative practice concluded that the high-quality abiotic properties of the restored mined fell within the range of the unmined lands, the added topsoil layers supported new root growth; and consequently, supported viable cattle reproduction (Bennett et. al. 2021). In fact, regenerative cattle grazing can be an intermediary process to restoring mine landscapes toward woodland-pasture landscapes and then complete woodlands through active management and a seasonal rotation of grazing to promote select area tree growth (Uytvanck and Verheyen 2014). Livestock feces can also act as a rich topsoil nutrient for the establishment of a healthy topsoil mix (Pasture Project 2021).

In contrast, the development and growth of healthy fauna tend to be an extreme challenge when it comes to restoring degraded landscapes according to Cristescu et al., who reviewed the findings of 71 publications on fauna recolonization across Australia (2012). Species density and richness tend to be significantly lower on rehabilitated landscapes like mines, and even more so when native species were grown (Cristescu et. al. 2012). The irony is that while the rehabilitation of degraded lands after mining is comprehensively understood, there continues to be a significant number of cases specific to the Australian context where adequate rehabilitation is neglected (Lamb et al. 2015). This speaks to the importance of adequate restoration practices as eluded to in the US Forestry Reclamation approach, and to re-establishing a healthy ecosystem dynamic for carbon sequestration opportunities.

Given the extent of environmental disturbance and novelty of mined landscapes, and the challenges associated with re-establishing holistic ecosystems with their native physical and biophysical, Hobbs (2017) propose hybrid (reversibly different) or novel (irreversibly different) ecosystems. The idea adopts radically different natural characteristics in order to adapt to the newly created environmental condition, yet be able to promote ecological services (within feasible management regimes and a rational mapping approach of a potential new landscape composition). This approach rationalizes the safety, stability, and new ecological functioning of a rehabilitated landscape and explores mine reclamation alternatives as a means to incentivize restoration altogether.

2.2 Industrial Agricultural and Coastal Landscape Restoration

The intensity of forest felling in Queensland, Australia is incurring a chain reaction of ecological degradation from the loss of significant carbon sequestration capacity, erodible landscapes with sediment runoff and contributing to dryer climates and the wider climate crisis (Yates and Hobbs 2000). After forest cover is felled, one of the predominant uses in Queensland, particularly along the coast, is industrial agriculture (Yates and Hobbs 1997). The establishment of woodland forest vegetation is critical to enhancing biodiversity and preventing dryland salination. Across a study examining Eucalyptus woodland regeneration over 519 agricultural sites in Victoria, Australia, the factors that reduced the probability of regeneration included intensive past land use (cultivation), regular livestock grazing, increasing distance to remnant trees, and high cover exotic annual vegetation (Dorrough and Moxham 2004). The study concluded that the success of natural regeneration of forest cover is dependent on active management approaches, including the prohibition of grazing or intermittent grazing regimes, which significantly increases the likelihood of forest cover regeneration (Dorrough and Moxham 2004). Understanding the select factors to increase the rate of success of transforming past agricultural lands to forest canopies provides increased opportunities for proper environmental planning.

While landscape clearing of woodlands and degradation for grazing and other agricultural processes are extremely well documented, there is a lack of literature exploring woodland regeneration and restoration techniques as it relates to diversity structure and function (Yates and Hobbs 1997).

Agricultural intensification, the same kind observed along the coast of Queensland, dramatically alters and homogenizes the landscape, endangering biodiversity, increasing soil degradation, and water body salinization (Krebs et al. 1999; Hendrickx et al. 2007; Billeter et al. 2008). This loss of landscape character includes the degradation of wetland landscapes along coastal Queensland, Australia, which are well understood across their human and wider biological functioning. In the context of wetland restoration, Moreno-Mateos and Comin (2010) develop an objective framework for restoring wetland systems, which can guide the restoration of Queensland coastal landscape in its extensive scale. This methodological framework includes identification of local needs of a wetland, the scale of the created wetland relative to its objective, to take up sub-catchment, catchment, or regional water flows, understanding conflicts and capabilities where the restoration or creation of wetlands serves multiple purposes, the creation of a general strategy based on aforementioned priorities (Moreno-Mateos and Comin 2010). While it requires a higher level of active management, the preferred strategy for developing wetland objectives is a multi-pronged approach that would promote heterogeneity in the landscape and provide multiple services like water flow take up and biodiversity replenishment (Moreno-Mateos and Comin 2010).

In a landscape planning study across regions of South Sweden, areas that suffer intense coastal eutrophication due to agricultural practices results from scenario modeling proved that the changes in agricultural practices (tunning, time of fertilization and ploughing, and changed crop cultivation) have the opportunity to reduce nutrient loads into the sea by 30% in comparison to 5% by simply recreating wetlands (Arheimer et al. 2004).

A diversified agroecological system approach, an anti-thesis to the existent and predominant industrial agricultural practices of input-intensive crop monocultures, industrial-scale feedlots, and widespread fertilizer use, can reverse the effects of degrading landscapes into a more long-term fertile, healthy, biodiverse agricultural landscape (Frison 2016). The ensuing fundamental change of the land use practice will surely have reproductive effects on all adjacent landscapes and in the context of this chapter, the Great Barrier Reef.

With regards to the best management approach for mitigating the loss of agricultural pollutants to streams, the abundance of riparian buffers and manure storage structures proved to be the most effective year-round strategy for reducing nutrient concentrations in riverine systems (Pearce and Yates 2017). Tile drainage and other managerial BMPs are secondary methods for reducing nutrient runoff (Pearce and Yates 2017).

To date, there is a dearth in the literature on sustainable coastal agricultural practices as it relates to climate change and one of the main issues behind its practicalities is farmer knowledge. Therefore, the inclusion and participation of farmers in climate change coastal landscape policy setting (specifically as it relates to coastal agriculture) is necessary to tether direct practical action (Tharani Gopalakrishnan et al. 2019).

In response to the degrading water quality from land-based pollutant sources specifically as it relates to the intensive agricultural practices, there are two major Great Barrier Reef plans that set out ambitions to decrease these pollutant sources. The Reef 2050 Long-Term Sustainability Plan sets out that “over successive decades the quality of water entering the Reef from broadscale land use has no detrimental impact on the health and resilience of the Great Barrier ‘Reef’, along with managing associated targets for water quality and land catchment management” (The State of Queensland and Commonwealth of Australia, 2003; Reef Water Quality Protection Plan Secretariat, 2009, 2013b). The Reef Water Quality Protection Plan (2003) is specific in its provision of a collaborative and strategic approach for water quality improvement through best management programs and voluntary methods and incentives farmers can take to improve water quality (Queensland Government 2015c; Department of the Environment 2015c). However, as of 2014, there continue to be poor trends to water quality management, including (i) increased uptake of BMPs, (ii) continued overall loss of wetlands and riparian areas, (iii) modeled… reductions in terrestrial pollutant loads entering the GBR, and (iv) continued poor condition of the inshore marine environment (Queensland Government 2015a, b). While land-based pollution reduction strategies are well understood, such as better surface and erosion control during grazing and reduction of excess applications of nitrogen use during sugarcane, cotton, and banana plantations, the socio-economic factors of altering current practices to best management practices are the challenge.

Kroon et al. (2016) make several comprehensive recommendations for future directions regarding land-based pollution control methods, including spatial and policy implications. These include identifying management practices and/or land uses with acceptable pollutant export rates; having effective incentives for the adoption of these practices and/or land uses; combining different policy instruments to reduce diffuse pollution from agricultural land uses [given the scale and complexity of the issue]; harmonization of multisectoral policies to protect GBR water quality [given the fact that there are 26 federal and Queensland government acts]; and a transformation all together of the existing land uses into more productive landscapes as well as the integration of modern agricultural products (Kroon et al. 2016).

2.3 *Coral Reef Regeneration*

Reef systems and coral community responses vary significantly depending on the intensity, and time-scale of disturbances, and while reef fragility has been exhibited on the human time scale, over millions of years, coral reef systems have demonstrated robustness to disturbances (Hughes 1989; Brown 1997). Ecological theories attribute the diversity of corals in a reef system to recurrent disturbances that create communities in various stages of recovery (Connell 1978). Furthermore, recent studies point to the coral capacity of acclimatization and adaptation to rapid ocean temperature changes, specifically with heat-tolerant coral colonies forming partnerships after heat events (Baker 2001, Kenkel and Matz 2016). On the topic of coral community recovery, Gilmour et al. (2016) highlight the capacity for coral reefs to naturally recover if isolated from chronic anthropogenic disturbance after observing an isolated reef on the northwest coast of Australia that had undergone severe bleaching and close to total coral cover loss. The surviving corals grew to maturity and effectively reproduced returning the system to existing conditions (Gilmour et al. 2016).

The reality that global coral reef systems face a range of chronic anthropogenic disturbances from climate change and ocean warming to nutrient and sediment runoff polluting ocean waters cannot be ignored on a present time scale for fear of complete ecological collapse. Rinkevich (2008) argues that the reefs' future is centered on the omnipresent acceptance of restoration, an 'active' management instrument. The Society for Ecological Restoration International Science and Policy Working Group (2004) defines restoration as 'the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed… [and] attempts to return an ecosystem to its historic trajectory'. Akin to the forest silviculture program and taking precedence from terrestrial forestation, the coral gardening strategy represents a recent approach to coral species regeneration where on/off-site coral nurseries are formed and species are transplanted to degraded sites for restoration (Epstein et al. 2003). This practice revolves around an active management and restoration process by which an establishment of large-scale seedling, transplant, and decolonization process for large-scale reef degradation can be facilitated (Rinkevich 2008).

Similarly, Bostrom-Einarsson et al. (2018) conducted a comprehensive review of 319 coral restoration studies and summarized the leading restoration methods into ten approaches outlined in Table 1. He found that the majority of methods involve some sort of coral fragmentation or transplantation of coral fragments (70%). They also realize four major conclusions, including (i) coral survival is high; (ii) survival rates and growth are depending on location and species type and therefore restoration approach and materiality need to be dependent on project objectives; and (iii) most projects tend to be small scale (less than 1 ha) and over a short time frame period with few strategies exhibiting characteristics to be scaled (with the exception of coral larvae dispersal) (Bostrom-Einarsson et al. 2018). The fourth conclusion, like other ecological restoration methodologies, is the fact that coral restoration suffers from a lack of clear objects (as a result of state and local objective overlapping), appropriate

Table 1. A compilation of active reef restoration techniques (Bostrom-Einarsson et al. 2018)

Intervention	Definition	Other common terms
Direct transplantation	Transplanting coral colonies or fragments without intermediate nursery phase	Coral tipping, post-disturbance repair
Coral gardening	Transplanting coral fragments with an intermediate nursery phase	Population enhancement, asexual propagation
Coral gardening—Nursery phase	Transplanting coral fragments with an intermediate nursery phase (used to describe case studies that only detail the nursery phase)	
Coral gardening—Transplantation phase	Transplanting coral fragments with an intermediate nursery phase, including outplanting juveniles raised in the nursery (used to describe case studies that only detail the transplantation phase)	Outplanting
Coral gardening—Micro-fragmentation	Transplanting micro-fragments from massive corals, with an intermediate nursery phase	
Substratum addition—Artificial reef	Adding artificial structures for purposes of coral reef restoration	Other terms: Engineered structures
Substratum stabilization	Stabilizing substratum to facilitate coral recruitment or recovery	
Substratum enhancement—electric	Enhancing artificial substrata with an electrical field or direct current	
Substratum enhancement—Algae removal	Enhancing substrata by removing macroalgae	
Larval enhancement	Using sexually derived coral larvae (often produced from eggs and sperm in in situ flow-through facilities) to release at the restoration site, after intermediate holding phase	Larval propagation, sexual propagation

monitoring, reporting for adaptive learning, and the result of these compounded findings, a poorly designed project (Bostrom-Einarsson et al. 2018) (see Table 1).

While the above research is seminal in understanding the GBR condition, coral recovery science, and restoration efforts, this restoration and design research effort takes one particular study as the breaking ground for exploring the Great Barrier Reef's systemic resilience. Hock et al. (2017) identify 100 reefs accounting for 3% of the Great Barrier Reef that are exhibiting characteristics of healthy systems and capable of promoting recovery located in areas that are cool, protected from crown-of-thorns starfish predation, and well connected to other reef systems through ocean currents with the capacity to supply larvae (fertilized eggs). While the study claims these connected reefs maintain a level of resilience that may help [the Great Barrier Reef] bounce back from disturbances (Hock et al. 2017), this research proposal underscores bounce forward resilience (transformation or the capacity to renew and re-organize in the face of disturbance) as the normative ideal (Meerow et al. 2016).

Realizing the scale of the Great Barrier Reef and extrapolating these findings further points to a clear conclusion that while many of these restoration methods explored can help on a small local scale (including as public education opportunities), a larger scaling of coral regeneration is critical. The larval enhancement and dispersal approach lends itself to that opportunity and especially when considering recent technological developments and research like drones, Larval Bots developed by researchers at the Queensland University of Technology (QUT) to deliver coral larvae to reefs for reseeding. The ongoing concept and trial entail capturing coral larvae during the annual spawning event of corals, rearing the larvae for several days, before releasing them en masse when they are ready to settle through drone operation on damaged reefs (Techrepublic 2019). The second set of drones is also using advanced camera technology beyond the human eye to monitor high-definition changes to coral health in the GBR (Scott 2021). However, the advances are not beyond their challenges, including the limited amount of coral spawn, identifying the most suitable reef resettlement locations requiring the use of artificial intelligence, and instantaneous computer vision to provide relative independence for widespread drone restoration (Techrepublic 2019). The combination of small-scale restoration and large-scale action has the opportunity of bridging public education and any gaps between management actions at the local and state management levels.

3 Methods

The project methodology merges layers of socio-ecological analysis across the land, coast, and reef systems, through both literature and analytical mediums, in order to develop a pragmatic and novel approach for the landscape restoration of the Great Barrier Reef. More specifically, the methodology takes form across four phases; (i) a literature and policy review as outlined above of restoration practices for the project regional contexts, (ii) a field study of select sites to guide the scale and design thinking approach, (iii) GIS analysis and 3D modeling of landscape sites to acutely understand

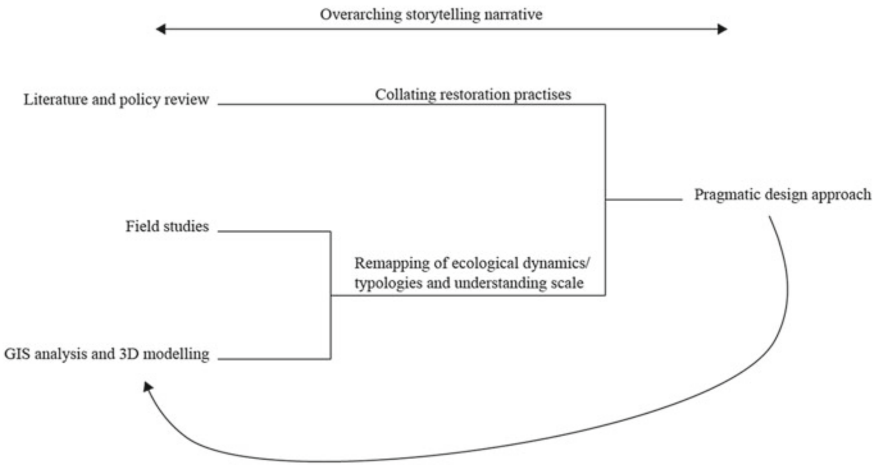

Fig. 1 Research methods hierarchy

spatial dynamics and connections, and (iv) a pragmatic design approach reorienting landscape uses and facilitating socio-ecological resilience. The project also uses an overarching story-telling approach to present landscape system connections and the severity of the issues to a wider public. Ultimately, the aim of this design restoration proposal is to not only establish a baseline of meaningful restoration approaches that holistically engage with biotic and abiotic for the Great Barrier Reef but also explore a methodological presentation medium that embodies the time-sensitive dynamism of landscape processes (see Fig. 1).

3.1 Literature Review

A high-level literature review first examines the landscape practices that continue to impact the Great Barrier Reef, a connected story across land-intensive coal mine activities, coastal industrial agriculture, and then bleaching events as a result of ocean warming on the Great Barrier Reef. This spatial connection begins to establish an understanding of scale and restoration interventions that are needed to facilitate socio-ecological resilience, particularly for reclaiming mine landscapes, reforesting coastal landscapes, and shifting industrial agricultural practices to sustainable means while taking into account water flows, and then regeneration of coral reefs on a large scale. A more comprehensive review as outlined in the section prior delves into these restoration practices and breaks down their capacity to create a more resilient ecological system. The restorative techniques also conceptualized on a degree of stewardship opportunities for a wider public engagement that realizes the scale of the issue. And while the overall intent is to produce solutions on a larger and holistic system scale, the pragmatic approach layers categorize these restoration practices as modular time-based design interventions.

3.2 Field Approaches

The secondary phase of the design research relied on field studies as a means of documenting landscape typologies from land, coast, to oceanic reef sites. The landscape architecture (design thinking) discipline inherits a rich tradition of field studies that stem from the ecological sciences. The method utilized photography, underwater videography, and drawing, to document and communicate a narrative of ecological change and to gain an appreciation of scale. The sites examined included sugarcane agricultural fields, Daintree national Rainforest (to build a repertoire of woodland and tropical species in some of the local regions), and a couple of underwater reef sites, including Agincourt and Flynn reefs. This background documentation was used twofold; as a means to understand scale, material, and biotic life for design restoration proposals (the tangible components); as well as to advance opportunities for public mobilization and designs that would increase access and legibility in the protection of reef sites and climate mitigation. The collected photographic imagery, particularly of underwater reef landscapes, was used throughout the public communication piece of this project to connect the audience, create an experience, and support the storytelling method of the project (described as the last overarching method).

3.3 2D and 3D Data Analysis

The tertiary phase of the research builds a spatially analytical framework for the existing context through landscape characterization and GIS mapping. This process investigated the most pressing anthropogenic impacts on land and in water to the Great Barrier Reef in Queensland, Australia, as well as exploring reef resilience characteristics. Following the three themes and spatial areas of study, land, coast, and deep-sea, the primary layer focused on understanding mining processes (particularly coal mines) and extraction in Queensland, Australia. This included the layering of all types of mines in the region, the type of resources being extracted, transportation lines, ports, and shipping data among other relevant digital information. The second atlas map is built on areas that have been cleared of forest for the past three decades, existing agricultural uses, erosion-prone areas, areas of high chemical concentration in the ocean, and reefs with COTS outbreaks. The third mapping exercise focused on deep-sea connections and explored natural flow patterns, such as reef connectivity and larvae dispersal in order to generate new ways of design thinking for the restoration of dying reefs. This also included the 100 reefs identified by Hock et al. (2017) as exhibiting characteristics of healthy systems and capable of promoting recovery in local areas as well as reef areas that are under threat due to human uses and climate impacts. The dynamic change and flux of ecologically valuable landscapes, particularly those that are rapidly degrading due to climate change, require a deeper level of understanding (as invisible and visible flows and processes) if landscape design practices intend to offer meaningful solutions. A University of Pennsylvania landscape architecture symposium, Simulated Natures organized in 2015, is used as precedence and explores these ideas in light of new computational developments through flows (modeling the invisibles), agents (designing for the invisibles), and indicators (revealing the invisibles). Therefore, the reef atlas aims to map these flows as a means of enhancing the capacity for resiliency (see Figs. 2, 3, and 4).

These atlas maps were all curated and represented as dynamic map drawings as opposed to static imagery through the use of time-sensitive data and animations in the public presentation. The drawings on the regional scale were used to represent the larger anthropogenic issues to the Great Barrier Reef from the amount of carbon-intensive mines, tree felling areas, to intensive agricultural coastal lands.

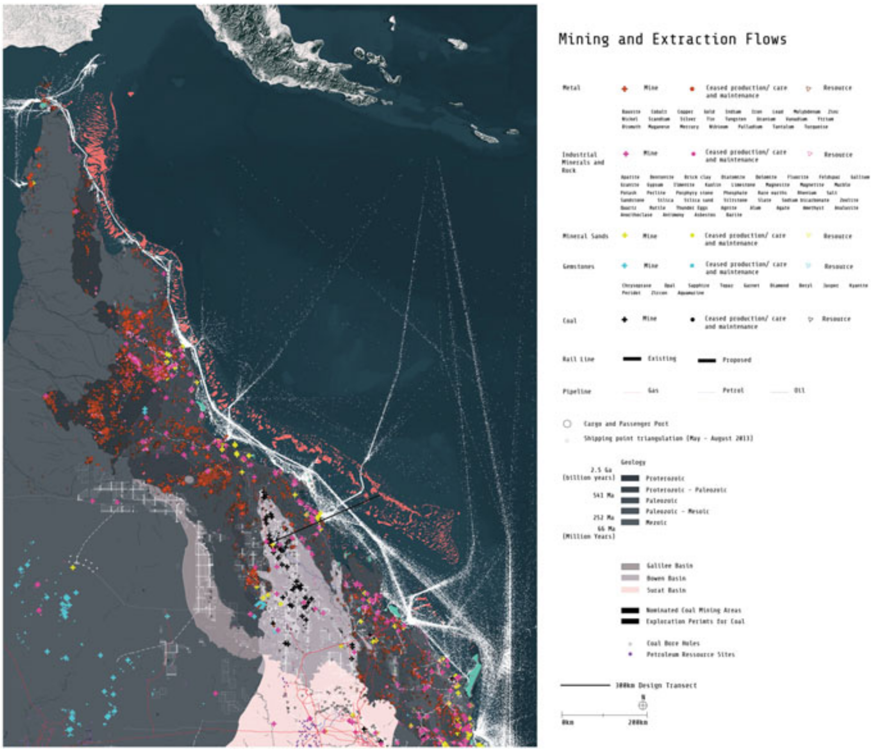

Fig. 2 Mining and extraction flows

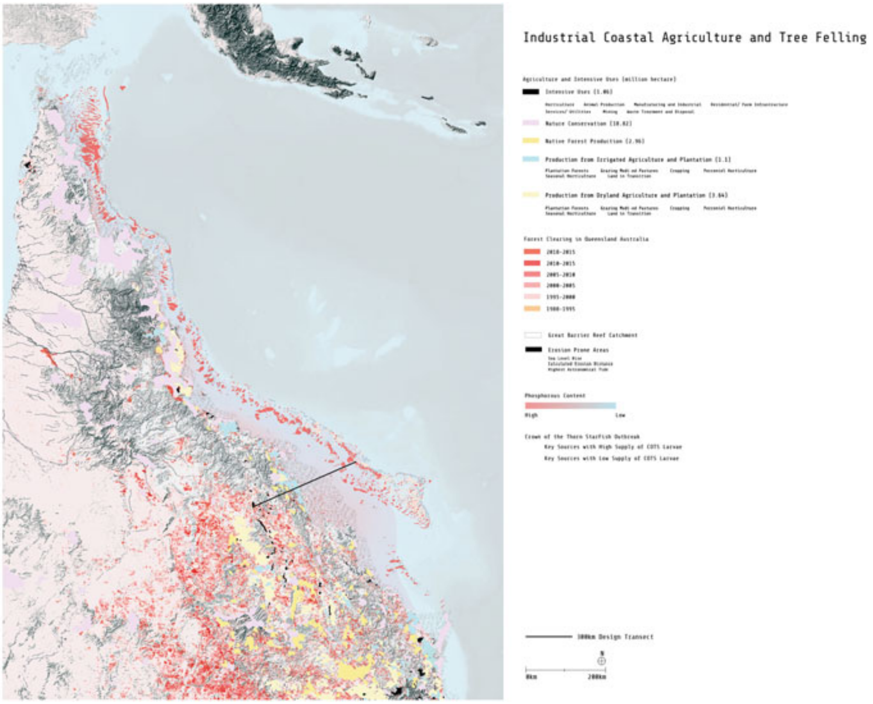

Fig. 3 Industrial coastal agriculture and tree felling rates in Queensland Australia

Three selected landscape sites (later discussed in the proposal section of this chapter) are further exploded into 3D models using digital elevation data in the design program Rhinoceros for a high-definition spatial analysis. For example, in the context of mine and coastal landscape restoration, this enabled topographic, water flow, and sunlight analysis on the landscape using additional scripting plug-ins, and to then be able to reshape and transform landscapes and other built forms according to applied restoration practices. The analysis is then re-applied onto the designed landscapes to evaluate the restorative changes.

3.4 Pragmatic Design Restoration Approach and Storytelling

Through a landscape architecture and regional planning lens, the proposal is ultimately shaped as a pragmatic design exercise. This means creatively balancing all of the above research findings across literature review, field studies, and landscape data analysis and generating design changes across the Great Barrier Reef landscape and its associated coastal and land-based practices. This is an iterative process and involves drawing and modeling to achieve a socio-ecologically sensitive approach.

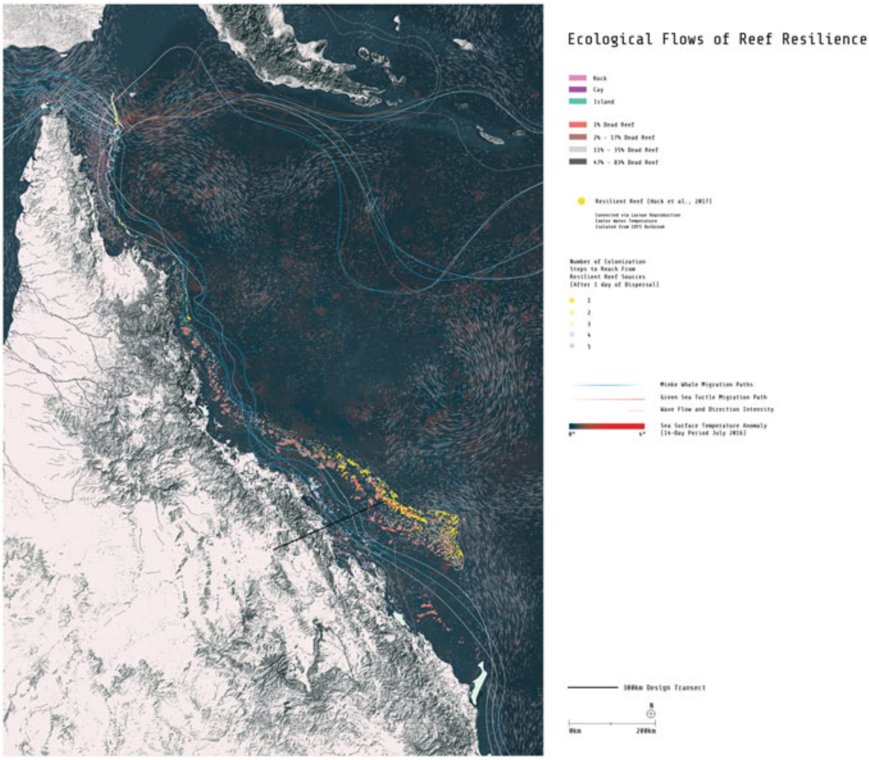

Fig. 4 Ecological flows of reef resilience

Finally, given its design nature, the project reveals these interconnected and complex landscape connections of the Great Barrier through a means of storytelling during a public exhibition presentation. The presentation is narrated through the lens of a resource extraction corporation (responsible for mining, logging, and industrial agriculture) having been made responsible by a high court for the destruction of the Great Barrier Reef and responsible for the restoration from land, coast, to deep-sea of damaged landscapes in order to save reef ecologies. This curation method heightened the experience of the audience and revealed this project to be about the reality of anthropogenic disturbance and more than a singular coral ecology study. The presentation method also acknowledges the governance, political, and corporate structures at play, that are necessary to be engaged with, should restoration proposals have a meaningful impact. Animations throughout the presentation engaged the time component of proposed interventions and added a projective element to the design restoration (see Figs. 5 and 6).

Fig. 5 Mining landscapes on Queensland Australia

Fig. 6 Coastal industrial farming and reef landscapes

4 Restoring a Manufactured Landscape and Toward a Natural System Dynamic of the Great Barrier Reef

In summary, intensive mining and industrial agricultural disturbances are impacting the development of the Great Barrier Reef, causing its collapse. GIS mapping and analysis show that these activities continue to harm this ecological system, ultimately affecting the earth system dynamic in Queensland, Australia.

The ecological restoration of the Great Barrier Reef involves necessary interconnected operations from Queensland's mining landscape, coastal intensive agricultural uses, and finally coral ecology regeneration. Three sites are selected: Goonyella Riverside Mine, Hay Point Coal Terminal, and Molar reef, across a 300 km transect, which are emblematic of the larger regional issues in this landscape to propose alternative restorative configurations for an ecologically productive identity via existing to novel landscape architecture and design restoration strategies. There is an attempt at communicating design representation as processes and systems over time in contrast to static architectural representation through iterative images that capture the nuances of regional geographies and dynamic landscapes.

4.1 Reclamation and Reforestation of Goonyella Riverside Mine

There is a strong irony to the fact that while millions and billions are spent on coral reef restoration campaigns, the Australian Government continues to permit and allow carbon-intensive coal mine development within a few hundred kilometers of the Great Barrier Reef catchment area (an increasingly becoming outdated source of energy), and among other mine extraction processes. This is the culprit that is contributing to climate change and ocean warming, causing bleaching and deteriorating the coral ecologies across a 2300 km span. This does not discount the intensity of port development and shipping navigational channels that continue to tear through the GBR catchment area.

Therefore, the primary focus is on the Goonyella Riverside coal mine in Queensland, Australia, with a depth of 100 m where a reforestation strategy is proposed. The idea is to return the landscape to its historic natural trends and also operationalize to sequester carbon and support climate mitigation that is impacting the Great Barrier Reef as well as counteract the rates of tree felling in the region. The primary strategy toward returning the mine condition to its ecologically productive state involves the topographic manipulation and fill given the mine's sharp ridges and terrace-like stepping as a result of mine operations. The secondary purpose of this strategy is to promote new microclimate conditions through slope adaptations and waterbed creation, by which biodiversity can prevail. The primary fill to cover up existing rock faces comes in the form of dredge material from shipping channels in the GBR heritage area presenting a novel opportunity. Currently, sludge and other dredge materials are being dumped into the Great Barrier Reef region covering and choking coral reefs.

The proposal explores digital techniques of analyzing topographic formation in order to optimize planting schemes and desired microclimate creation through novel 3D modeling and topographic analytical tools. Variables including height, slope, and degree of solar exposure based on the region's weather data dictated the type of microclimate being created and necessary for specific woodland forest types, native to the region and ultimately serving as a method of analysis for optimizing topographic forms (see Fig. 7).

In order to create the necessary topsoil conditions for a productive landscape, regenerative cattle grazing is programmed with a layer of hay-mulch added onto the new land. This begins to remove pressure from coastal industrial farming as well as initiate topsoil formation through feces decay.

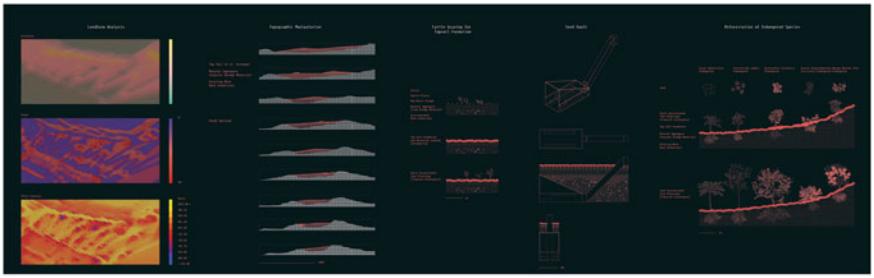

Fig. 7 Restorative strategies and microclimate development for relic coal mine landscapes

Furthermore, there can be an opportunity to engage public stewardship with the creation of research center huts that have open public access and that house seeds of a new planned forest. A citizen science approach can generate opportunities for landscape restoration monitoring, further planning, and public education for the acceptance and understanding of large-scale restoration.

4.2 Restoration of Coastal Hay Point Coal Terminal

The spatial examination of the industrial farming front reveals an artificial patterned landscape paralleling kilometer long-streams and coastal ocean landscape with no to minimal buffers. The select site, Hay Point Coal terminal, is a key node for coal shipment and is surrounded by cattle grazing operations.

The regenerative process is initiated by analyzing the water flow patterns through landscape digital modeling. This knowledge begins to inform the spatial re-organization of manufactured coastal landscape patterns in order to mitigate poison runoff into the Great Barrier Reef Heritage area. New embankments are subsequently proposed (using shipping channel dredge material as an opportunity) and reroute the agricultural runoff flows from river and ocean zones (see Fig. 8).

On the newly formed slopes, native coastal tree species from red mangroves to Omreau bottle trees are introduced to stabilize the topography and counteract tree felling for agricultural land use conversion. Furthermore, an observatory tower is proposed to deck over this new landscape where farmers and locals are able to visualize new land patterning and the beginning of a rerouted network of water flows. The new undulating embankment wraps around the coastal site like a necklace and offers a new connected path system for public engagement.

As part of a spatial policy scheme, the proposal advocates to work with local farmers and to initiate holistic agricultural management which includes the analysis of soil mediums in order to promote appropriate agriculture plantations (sugarcane versus cotton native to the region), and ultimately to minimize chemical water leaching potential. Holistic management also includes seasonal grazing where ground

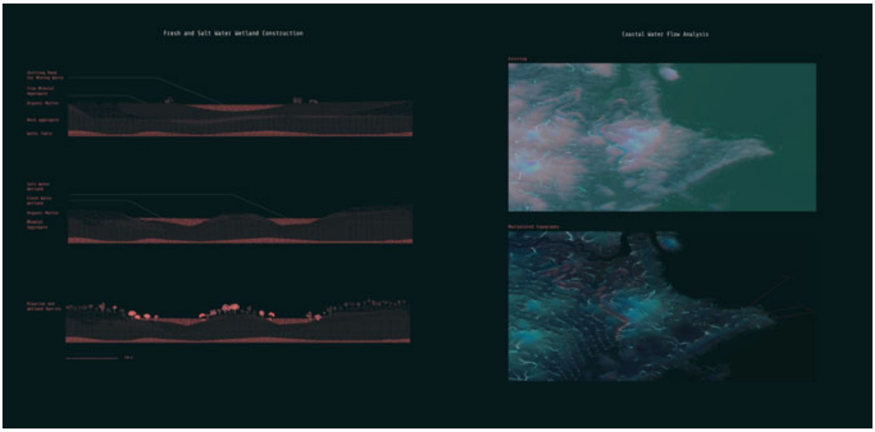

Fig. 8 Coastal water flow analysis and re-configuration for sustainable water drainage and runoff capture

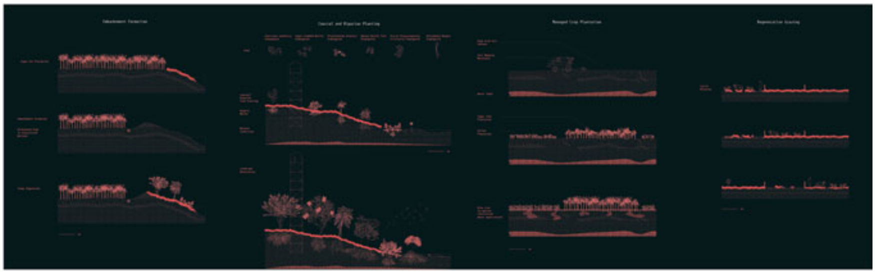

Fig. 9 Restorative coastal landscape strategies, regenerative grazing, and tree coastal reforestation

cover is not completely decimated to promote stabilization of coastal lands from runoff and increase carbon sequestration (Fig. 9).

Using the existing agricultural land use patterns and modeled water flows, key drainage lines are designed approximately following the landscape contours, and ultimately laying the foundation for a new spatial restructuring of industrial agriculture patterns. As a tertiary layer to this spatial restructuring that connects with the key lines and creates an ocean buffer, fresh and saltwater wetlands are re-introduced in lieu of the existing coal tailing ponds on site. The layering of these landscape architectural strategies proposes a healthier flow pattern.

The coastal restoration chapter is concluded with the introduction of new farming opportunities, coral farming, along the existing 2 km coastal bridge that originally facilitated coal shipping on site. Both existing and novel farming opportunities are explored; from electrically conductive steel meshes, coral fragmentation on floating tree units that are capable of regenerating coral species up to 50 times faster, down to hand-size tetrapods where coral larvae are seeded, and then transported off-site for planting. Along the bridge and through the ocean's clear waters, farmers and locals are able to claim new agency to these artificial and regenerative processes.

4.3 Regeneration of Coral Ecologies on Molar Reef

With the restructuring of Queensland, Australia's manufactured landscape system, coral regeneration on-site begins to be more impactful. While corals have a tremendous capacity to recover after disturbance, the rates at which disturbances have been impacting the reef system are irreversible and require adaptive management strategies to facilitate a resilient trajectory. The idea for coral regeneration is to engage on an immediate present time scale where first a spatially and technologically integrated slew of sensors provides feedback of coral reef conditions. Installed underwater camera domes and drones are proposed to provide time-sensitive imagery of bleaching events as well as COTS outbreaks. Sea surface and depth sensor products monitor both water and temperature quality through the use of existing technologies, including chemical composition, turbidity, light, and radiation intensity sensors.

The proposal begins to capitalize on reef resilient capacity by rearing coral larvae in nets during annual coral spawning events and using this natural reproduction as a catalyst for greater regeneration. This is where Hock et al. (2017) study identifying 100 reefs, accounting for 3% of the Great Barrier Reef that are exhibiting characteristics of healthy systems and capable of promoting recovery can be operationalized. One of the main criteria is the high connectivity to other reef systems through ocean currents with the capacity to supply larvae (fertilized eggs). Preserving these reefs sites with stronger protection measures and then collecting, rearing, and dispersing their larvae is a clear opportunity toward natural regeneration across the Great Barrier Reef region. Reared larvae are then released on dead or dying reefs based on collected sensor data speeding up the regeneration process via underwater drones (technology currently being prototyped by the Queensland's University of Technology). Similarly, a second set of drones is programmed to target COTS outbreaks and release a lethal injection. While smaller target interventions like individual coral plot planting or the use of tetrapods may be effective for individual reef sites, the reality is, there is a need for scaling of restoration methods in order to effectively regenerate reef systems across the 2300 km span, like the use of novel drone technology for larvae dispersal. And a targeted approach of restoring reefs that are most connected to others via larvae reproduction, first, is in order to facilitate natural coral succession.

5 Conclusion

The rate at which anthropogenic disturbances and climate change are impacting many earth systems like the Great Barrier Reef is surpassing its regenerative capacity. The design restoration research critically explores the dynamics between the time-sensitive ecological processes, and remaps the landscape story to represent holistic impacts, ultimately asking, what are practical yet meaningful restorative approaches for regenerating massive, degraded landscapes like the Great Barrier Reef? How can we better engage with biotic and abiotic earth system dynamics through restoration practices, digital tools, and design methodologies?

The narrative advocates for a new regenerative connection between land (reforestation of carbon-intensive coal mines contributing to climate change), coast (spatial restructuring of coastal industrial agricultural lands polluting the GBR catchment area), and deep-sea (regenerative approaches for coral ecologies that are collapsing primarily due to ocean warming). The selected sites are emblematic of the larger regional issues in the region and are ultimately what is facilitating the degradation of the Great Barrier Reef. A library of restoration practices is collected by which a range of existing to novel landscape architecture strategies are layered to facilitate an ecologically resilient, connected, and productive landscape. The restoration strategies are mapped, drawn, and analyzed using 3D design modeling methodologies in order to spatialize and scale action plans.

Although, significant time and human resource investment are required at the outset of proposed restoration processes, justly designed restoration plans will promote a natural succession and resilience across the Great Barrier Reef and its associated landscapes. While on the one hand, the design philosophy is to restore and reconnect these massive landscapes on a holistic scale, the concept pushes for collective reflection on past action as well as agency on the present to future conditions through public access and legibility of proposed design interventions and real-time monitoring.

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International Climate Change Agreements: Setting a Global Agenda and Calling for Action

Sirisha Indukuri

Abstract The threat of climate change is a problem of the global commons and has brought together the international community to devise mechanisms for addressing it. The present chapter traces the trajectory of international conventions, frameworks and agreements that have set forth an agenda for global cooperation on climate change. The United Nations serves as an umbrella organisation with its key institutions at the forefront of propelling climate action today. The Vienna Convention and the Montreal Protocol, in the 1980s, were met with success in implementation and hailed as benchmarks of international collaboration. The Rio or Earth Summit of 1992 led to the adoption of the United Nations Framework Convention on Climate Change, which holds a Conference of the Parties every year. The most significant climate agreements to have resulted from the several Conferences of the Parties, are the 1997 Kyoto Protocol and the 2015 Paris Agreement. The push lent to the climate agenda by international agreements has paved the way for the emergence of regional groups, non-UN and non-state groups, which are slowly taking forward the mantle of climate action. The chapter further discusses factors that influence the course of international climate agreements. Despite such influence and resulting concerns, the existing global alliance is inevitable and essential to address the looming anthropogenic challenge of climate change. In conclusion, the chapter asks if there is a need to think of a different and alternative paradigm to see the world make a closer run to achieve its climate targets.

Keywords Kyoto Protocol · Paris Agreement · COP · International initiatives · Climate action

Abbreviations

AEBR	Association of European Border Regions
AR1	First Assessment Report

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CBDRC	Common but Differentiated Responsibilities and Respective Capabilities
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
COP	Conference of the Parties
FOGAR	Forum of Global Associations of Regions
GEF	Global Environment Facility
GHG	Green House Gas
ICLEI	International Council for Local Environmental Initiatives
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JI	Joint Implementation
LULUCF	Land Use, Land Use Change and Forestry
MEF	Major Economies Forum on Energy and Climate Change
MRV	Monitoring Reporting Verification
NAMAs	Nationally Appropriate Mitigation Actions
NAPAs	National Adaptation Programmes of Action
NDC	Nationally Determined Contribution
NGO	Non-Government Organisation
Nrg4sd	Network of Regional Governments for Sustainable Development
OECD	Organisation for Economic Cooperation and Development
OLAGI	Latin-American Organisation of Intermediate Governments
PPP	Public Private Partnership
REDD	Reducing Emissions from Deforestation and Degradation
SDGs	Sustainable Development Goals
SR 15	Special Report 15
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
ZICOSUR	Integration Zone of the Centre-West Region of Southern America

Climate change is a reality today, the existence of which is undisputed and no longer subject to scepticism. While the precise antecedents of the anthropocene[1] are still being drawn, there is a clear recognition that we are living in an epoch where the impacts of global warming and a changing climate are being felt universally albeit a bit differentially across the world (Dalby 2014; Arnell et al. 2019). In order to

[1] Anthropocene is defined in the Oxford English Dictionary as "the era of geological time during which human activity is considered to be the dominant influence on the environment, climate, and ecology of the earth".

deal with the challenges being posed, collective global or international action is imperative.

By its very nature, climate change is defined as a problem of "global commons"[2] (Stiglitz et al. 2001; Metz 2010), the effects of which reach all irrespective of territorial boundaries. The benefits accrued from minimizing climate change impacts, are "non-excludable" and "non-rival" and are simultaneously enjoyed by everyone without reducing the benefits for others (Chan et al. 2018).

The argument for global cooperation is strengthened further by other aspects. As the sources of greenhouse gas (GHG) emissions are distributed unevenly, the emissions contribution of an individual nation may appear small, but when aggregated with that of other nations, the quantum becomes significant. Likewise with various economic sectors, where the share of a specific sector may not appear to be very large, but when put together with other sectors, the contribution becomes sizable. In a global economic world where products are part of a worldwide supply chain, global and international cooperation is core to any efforts made to reduce emissions and promote a low carbon economy. Moreover, for any nation, the costs of the impacts of climate change will prove to be greater than the costs of avoiding it. Therefore, to receive benefits at the lowest possible prices, such cooperation is indispensable (Metz 2010; Stiglitz et al. 2001).

Yet another reason that calls for global cooperation is the need for compliance and enforcement. In the wake of the present "global commons" challenge, who ensures that nations transition to climate-friendly action? A binding international framework or agreement becomes the instrument that drives the formulation of such action and serves as a mechanism that promotes enforcement and compliance.

The existence of multiple stakeholders, uneven distribution of emission sources, the realisation of differential impacts over space and time, and unequal capacity to deal with implications are factors that set the stage for global cooperation (Stiglitz et al. 2001). Over the years, several suggestions have been advocated to help address climate change like (among others) its integration in the contributing sectors, use of market-based instruments, development of a global price for GHG emissions, and technological innovation and diffusion (OECD 2007). The push for the necessity to act is offered through global or international[3] cooperation.

1 Trajectory of Global Climate Cooperation

The United Nations (UN) has been at the helm of bringing together global cooperation to tackle the crisis of the environment, including climate change. The roots of global action for climate change can be pinned to the formation, in the early 1990s, of the Framework Convention on Climate Change. The background, however, was

[2] Global commons refers to shared resources that lie beyond the jurisdiction of individual nations.

[3] I use the terms global and international intermittently; while international refers to a coming together of more than one nation, global pans a more universal presence.

laid in the 1970s and 1980s with the growing international awareness about the world facing an environmental crisis. It was this recognition that led to the Stockholm Conference of 1972, the first major conference of the UN to address global environmental issues, which also saw the formation of the United Nations Environment Programme (UNEP). Later the Vienna Convention of 1985 brought attention to the protection of the ozone layer and made way for the Montreal Protocol of 1987 that set limits on the use and production of ozone depleting substances. Given its widespread adoption and effective implementation, the Montreal Protocol has been hailed as a successful example of international cooperation, even leading the former UN Secretary-General Kofi Annan to term it as "*perhaps the single most successful international agreement to date [in 2003]*" (UNEP 2019; McNeill 2020). It is amidst such backdrop that the agenda of climate change emerged at the global arena, as part of an existing yet growing concern for global environment and ecology.

Fuelled by the emerging consciousness and awareness on climate change, in 1988, the Intergovernmental Panel on Climate Change (IPCC), a UN body, was established to provide scientific information on the impacts, hazards and risks of climate change, as also to indicate possible responses to deal with it. The IPCC has 195 member countries and came out with its first assessment report (AR1)[4] on climate change in 1990. The two years that followed the release of the AR1 saw discussions and negotiations, which eventually led the UN General Assembly to arrive at a common framework for climate change (Metz 2010). Consequently, at the 1992 UN Conference on Environment and Development (UNCED) held at Rio de Janeiro, also known as the Rio Summit or the Earth Summit, a framework convention on climate change was adopted.

The Rio Summit was a milestone as it led to the formation of three key conventions on the environment, namely, (i) the Convention on Biological Diversity (CBD) to address the loss of biodiversity, (ii) the Convention on Combating Desertification (CCD) to address the problem of desertification, and (iii) the Framework Convention on Climate Change (FCCC) to address the consequences of climate change. Subsequently, each of the conventions has played a key role in taking forward its respective mandate and holds a Conference of the Parties (COP) once in two years (in the case of CBD, CCD) or every year (in the case of UNFCCC).

The UN has not only acted as a catalyst for global cooperation but serves as an umbrella organisation that has set up key institutions standing at the forefront for propelling climate action. The UNFCCC, established under its rubric, sits at the centre of climate institutions as the primary platform for holding discussions, negotiations and proposing actions (see Fig. 1).

[4] The IPCC prepares scientific Assessment Reports every few years and has so far produced five assessment reports with the sixth one under preparation by its working group and is expected to be released in 2021. The assessment reports are synthesis reports that offer a comprehensive review of the climate scenario. Additionally, the IPCC prepares Special Reports that assess specific issues and Methodology Reports, which serve as guidelines to create GHG inventories.

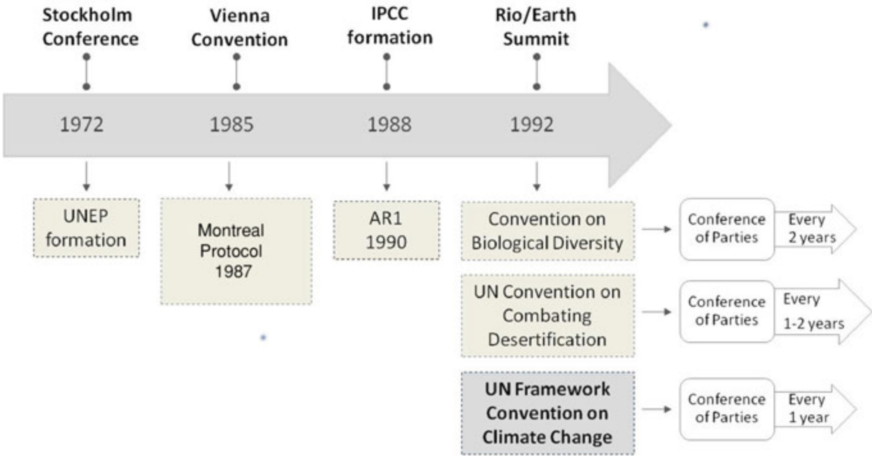

Fig. 1 Background of the emergence of international climate agreements

1.1 UN Framework Convention on Climate Change

Although established in 1992 at the Rio Summit, the UNFCCC came into force in 1994. Its goal is to "*stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climatesystem…Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner*" (UNFCCC 1992). The UNFCCC works closely with the IPCC, which in turn produces scientific reports to aid and support UNFCCC impart its functions and take informed decisions.

In its role as a framework agreement, the UNFCCC formulates principles, general goals and actions that countries should take as a precautionary measure to limit GHG emissions. It has also established institutions, a reporting mechanism and a system of review for further action. Premised on the principles of "*polluter pays*" and a "*common but differentiated responsibility*", the UNFCCC held developed countries accountable for greater emissions reduction targets based on the rationale that they were the bigger emissions contributors in the past, while special consideration was made for vulnerable, developing countries. Accordingly, the Annex I, Annex II, and non-Annex countries were defined and listed by it. The Annex I list comprises the industrialised economies and those belonging to the Organisation for Economic Cooperation and Development (OECD). It includes the European Union and the economies in transition from Central and Eastern Europe. The Annex II countries are the developed economies and the European Union, but exclude the economies in transition. The non-Annex nations are the developing countries. Specific emissions reduction targets are set for the Annex I countries[5] (a list that also includes the Annex II countries). In contrast, the Annex II countries (as distinct from the Annex I) are accounted for providing financial resources for developing nations or the non-Annex countries (ibid.).

Today, 197 countries have ratified the UNFCCC and are party to it[6]. Every year, a COP[7] is organised by the UNFCCC, and since inception it has held a total of 25 COPs (until 2019). It has also set up three financial instruments to support climate action: (i) Global Environment Facility (GEF)[8] funded (voluntarily) by the Annex II countries, (ii) Least Developed Country Fund and (iii) Special Climate Change Fund for financing adaptation.

1.2 Key Agreements of UNFCCC

The first COP of the UNFCCC was held in 1995 in Berlin, where negotiations were started to identify the countries that needed to be committed to emissions reduction. The negotiations resulted in the Berlin Mandate, according to which the Annex I countries were accounted for reducing their respective GHG emissions. Over the following two years, the emissions reduction goal was quantified and put forward at the Kyoto COP in 1997, to materialise into what came to be known as the Kyoto Protocol, one of the most significant agreements to come out of the UNFCCC COPs (Metz 2010; Chan et al. 2018).

1.2.1 Kyoto Protocol, 1997

The Kyoto Protocol proposed at the COP 1997 set specific quantified targets for emissions reductions for the Annex I countries of the UNFCCC, for the period 2008 to 2012 called the "*first commitment period*" (UNFCCC 1998, 2008). It came into force, however, only in 2005 after its ratification by the parties. The goal for the

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[5] The convention included in the Annex I countries: Australia, Austria, Belgium, Canada, Denmark, European Economic Community, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom of Great Britain and Northern Ireland, United States of America; and in the economies in transition it included: Belarus, Bulgaria, Czechoslovakia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russian Federation, Ukraine.

[6] A convention, agreement or framework is said to be ratified by a nation or country once it is approved formally by the parliament, cabinet or respective decision making body of the country and upon ratification the nation becomes a 'party'. Ratification indicates giving a formal consent to be bound by the agreement by virtue of being a part of it.

[7] The Conference of Parties (COP) is the decision-making body comprised of all the ratified nations or parties. A COP is named after the place where it is organised for the parties to come together for the annual meet.

[8] GEF is operated through the World Bank, United Nations Development Programme (UNDP) and UNEP.

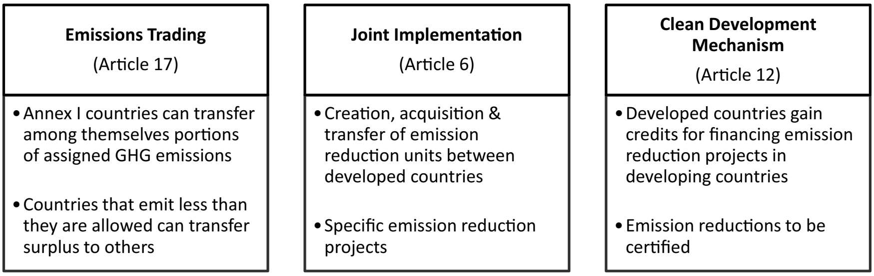

Fig. 2 Emissions reduction mechanisms under the Kyoto Protocol

commitment of Annex I parties was set as follows: with reference to the base year of 1990, a reduction by 5% in their overall national emissions from sources listed in Annex A[9] of the protocol. The individual country-specific targets were enumerated in Annex B of the protocol. Other parties or non-Annex countries could participate in different ways.

A system of compliance and reporting by the Annex I parties was outlined in the protocol, which provided three comprehensive and flexible mechanisms to operationalise emissions reductions. These were: (i) Emissions Trading, (ii) Joint Implementation and (iii) Clean Development Mechanism.

By means of Emissions Trading, an Annex I party could transfer its units to another Annex I party or vice-versa, that is, acquire units from another party. Joint Implementation (JI) allowed an Annex I party to invest in an emissions reduction project in another Annex 1 country and gain credits for the same. The Clean Development Mechanism (CDM) provided for Annex I parties to invest in emissions reduction projects in non-Annex countries, developing countries and gain the emissions reduction credits for it. The process of a CDM project involved various stages of project development, project implementation, certification, and approval of certified emissions reductions (CERs). What was important for CDM was that there had to be an element of 100% additionality. In other words, a CDM project had to be over and above a business-as-usual scenario, specifically designed for CDM purpose. An existing project could not be pitched as also a CDM project (ibid.) (see Fig. 2).

By means of participation in the above three mechanisms and through Land Use, Land Use Change and Forestry (LULUCF) activities, the Annex I parties could raise or lower their initial assigned amount or change the level of their allowed emissions over the first commitment period (UNFCCC 1998; UNFCCC 2008; Chan et al. 2018; Stavins et al. 2014). In 2005, negotiations commenced for a second commitment period for the Kyoto Protocol; these finally concluded in 2012 when the second commitment period was established from 2013 to 2020. While countries like the United States opted out of the Kyoto Protocol in the first commitment period

[9] Annex A of the Kyoto Protocol lists six green house gases: Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF6). It also lists the sectors and respective sources of GHG emissions; the sectors listed are energy, industrial processes, solvent and other product use, agriculture, and waste.

Kyoto Protocol

- Emissions reductions targets set for Annex I countries
- Target of reduction by 5% in overall national emissions from listed sources
- Base reference year of 1990
- Targets set for the first commitment period of 2008 to 2012
- Three flexible mechanisms provided for fulfilling emissions reductions targets
- Parties can change level of allowed emissions, with the flexible mechanisms & LULUCF

Fig. 3 Highlights of the Kyoto Protocol

itself and others like Canada, New Zealand, Japan were hesitant to extend into the second commitment period, notwithstanding the non-participation of some of the big emitters, many Annex I parties were able to fulfil their targets and committed to reducing their GHG emissions in the first and second commitment periods (see Fig. 3).

Post Kyoto, discussions began on the need for a reconsideration of the distribution of emissions reduction targets. The climate change conventions were hitherto premised on an equity principle and had not taken into cognizance the fact that over time many non-Annex countries saw a significant growth of their economy and a consequent increase in their emissions release. The problem of leakages could not be dismissed any longer. While Annex I countries reduced emissions, if the developing countries were not bound to reduce emissions, they would add back emissions (Stiglitz et al. 2001). In the wake of these elements, the COPs post-Kyoto saw the emergence of discussions and negotiations on relooking at the distribution of emissions reduction targets, thereafter making way for future agreements and frameworks that came into shape at the succeeding key COPs and later led to the significant Paris Agreement.

1.2.2 Post Kyoto

In 2007 the Bali COP was held where re-thinking began on the distinction between the Annex and non-Annex parties and the base reference year of 1990. At the same time, the discussions brought forth the need for setting up of a ceiling on global average temperature increase. The Bali Action Plan was formulated here and highlighted some key areas like Monitoring Reporting and Verification (MRV) by the developed nations, design of Nationally Appropriate Mitigation Actions (NAMAs) for developing countries, and Reducing Emissions from Deforestation and Degradation (REDD). It also called for adaptation action in developing nations and implementing measures to protect against climate change, including National Adaptation Programmes of Action (NAPAs).[10]

The discussions held at and those preceding the Copenhagen COP of 2009, resulted in the Copenhagen Accord, which was ratified by 100 parties and highlighted the proposition of keeping the global average temperature increase to 2°C (or even 1.5°C) above pre-industrial levels. Additionally, it proposed 30 billion dollars from developed countries for mitigation and adaptation in developing countries, adopting new mechanisms for adaptation, financing forest preservation, and technology transfer (Metz 2010; Chan et al. 2018). It also built the ground for setting up of the Green Climate Fund, established at the following Cancun COP in 2010.

The re-thinking on the distribution of emissions reductions targets, previously designed in the Kyoto Protocol got further concretised in 2010 at the Cancun COP. The discussions were instrumental in recognising that the enforcement mechanism as the one in the Kyoto Protocol (legally binding, collective emission targets and equitable sharing of emission reductions) would slow the goal of 2°C increase in global average temperature initiated in the Bali COP. This recognition led to new opportunities that would drive nations to adopt robust emissions reductions action (ibid.).

The discussion on targets re-distribution was furthered at the Durban COP held in 2011 and again, reiterated and outlined in the form of the Durban Platform for Enhanced Action, which highlighted developing a protocol or instrument that would have a legal binding and would apply to all parties(ibid.). In 2012 at the COP held in Doha, the parties agreed to extend the expiring Kyoto Protocol to a "second commitment period" from 2013 to 2020, which was notified as the Doha Amendment.

Going forward, the measure to extend the commitment period took further shape in 2013 at the Warsaw COP, the discussions of which were presented as the Warsaw Mechanism. The mechanism proposed establishing a timeline for all parties (both developed and developing countries) to offer Intended Nationally Determined Contributions (INDCs); where the INDCS would represent each country's planned mitigation actions (Chan et al. 2018). The proposition set the stage for the significant Paris Agreement that followed two years hence.

1.2.3 Paris Agreement, 2015

The most comprehensive framework for international climate policy post the Kyoto Protocol of 1997 is the Paris Agreement, which was formalised at the COP 21 held at Paris in 2015. At the centre of the Paris Agreement is a pledge and review of

[10] Climate change mitigation and adaptation are two types of broad overarching actions recognised to handle the climate problem. Mitigation refers to efforts that minimise emissions of GHG; whereas adaptation efforts aim to reduce the negative effects of climate change that will be experienced or, in other words, it means preparing for the negative impacts that are already being felt or will be felt.

Nationally Determined Contributions (NDCs) made by the parties. The NDCs are ten-year goals for climate mitigation set by each party and may include adaptation, finance and other measures. The agreement establishes a goal of "*global warmingwell below 2°C on pre-industrial average*" to pursue efforts to limit the temperature increase to 1.5°C. In revising the base reference level from 1990 to pre-industrial time, the agreement presents a more ambitious goal. In order to strengthen the global response to climate change, it offers a universal framework by obligating all parties to contribute to climate change mitigation and adaptation (Stavins et al. 2014; UNFCCC 2015; Streck et al. 2016).

Unlike the Kyoto Protocol, the Paris Agreement has adopted a more inclusive 'bottom-up' approach in terms of individual national targets (Chan et al. 2018). It does not set emissions reduction targets for individual parties, but formulates an overall climate change goal asking parties to contribute to it. The individual parties decide how and how much they can contribute to meeting that goal. In this sense, "it is directional, not prescriptive" (Rivett-Carnac 2020). The design draws on the "*principle of common but differentiated responsibility and respective capabilities, in the light of different national circumstances*". Thus, although it builds on the principles established in the UNFCCC, that is, "*common but differentiated responsibilities and respective capabilities* (CBDRC)", it specifies that it will be implemented "*in the light of different national circumstances*" (UNFCCC 2015). The share of total emissions, however, applies to all countries and not merely to the developed Annex I parties, as was the case with the Kyoto Protocol.

In order to keep a track on the overall goal, every five years the COP will take stock to review the progress in meeting it. Consequently, informed by the same, each party will update and adapt its NDCs to reflect '*a progression beyond the then current nationally determined contribution*'. The NDCs, therefore, are envisioned to increase over time and align as the '*highest possible ambition*' with changing capabilities. The agreement holds that setting ambitious targets and actions by some states will evince reciprocity from other states to raise their respective ambition levels (Streck et al. 2016; Chan et al. 2018).

The emissions reduction commitments in the form of NDCs represent a political aim rather than a legal obligation (Streck et al. 2016). The agreement lays communication, reporting and accounting by parties for their actions and results achieved in implementing NDCs, based on the element of trust and promotes '*environmental integrity, transparency, accuracy, completeness, comparability and consistency, and [ensuring] the avoidance of double-counting*' (UNFCCC 2015). The Paris Agreement came into force in 2016, effectively replacing the Kyoto Protocol. It is ratified by 189 (out of the 197 countries that are party to the UNFCCC).

A significant landmark in the international climate agreements, the Paris Agreement complements the global agenda for the 2030 Sustainable Development Goals (SDGs) where climate change (SDG 13) remains the strongest of challenges (see Fig. 4). It also recognises the critical role that non-state actors like the private sector, citizens and other state actors like regional governments, must play in transitioning towards a zero-carbon economy or net-zero emissions by 2050 (Wolfe et al. 2016; Rivett-Carnac 2020).

Paris Agreement

- Ten year climate mitigation goals "Nationally Determined Contributions" set by parties
- Overall goal of keeping global warming below 2°C; base reference level of pre-industrial time
- Increase in ambition with time and limiting temperature increase to 1.5°C
- All parties obligated to contribute to climate change mitigation and adaptation
- Communication, reporting and accounting by parties for results achieved in NDCs
- Recognition of the role of non-state actors and domestic, regional state actors

Fig. 4 Highlights of the Paris Agreement

While the Paris Agreement has provided a clearer direction for global response on climate change, the incentives for taking ambitious actions can be made more robust. The success of the Paris Agreement will depend on the ramping up of individual country NDCs and setting up of more ambitious targets.

1.2.4 Post Paris

The post Paris period has seen the hosting of four COPs (at Marrakech, Bonn, Katowice, and Madrid) and the initiation of discussions on newer issues like water related sustainability. A significant development post-Paris was the bringing out of the Special Report 15 (SR15) of the IPCC in 2018. The scientific report rationalises keeping the ceiling of global average temperature increase at 1.5°C than at 2°C. It argues that even with a 2°C goal, extreme events and other adverse effects will continue to plague nations.

The post Paris developments have pointed to the necessity of big and ambitious targets and actions that will bring emissions to net zero by 2050 and hold temperature increase to below 1.5°C. The subsequent discussions have called for countries to put forward ambitious commitments in the form of new NDCs and long term strategies for net zero emissions as also commitments to support the vulnerable nations and formulate ambitious adaptation plans. The push has been further strengthened with the publishing of the Emissions Gap Report 2020 and the Production Gap Report 2020, which provide the rationale for making such ambitious goals and commitments. The Emissions Gap Report 2020 reviews the gap between the predicted GHG emissions for 2030 and where it should be. The Production Gap Report 2020 discusses the gap between the goal set by the Paris Agreement and the projected production of coal, oil and gas as planned by countries (UNEP 2020; SEI et al. 2020). The trajectory of climate cooperation, thus, when seen in the above light, has constantly evolved with every key milestone (see Fig. 5).

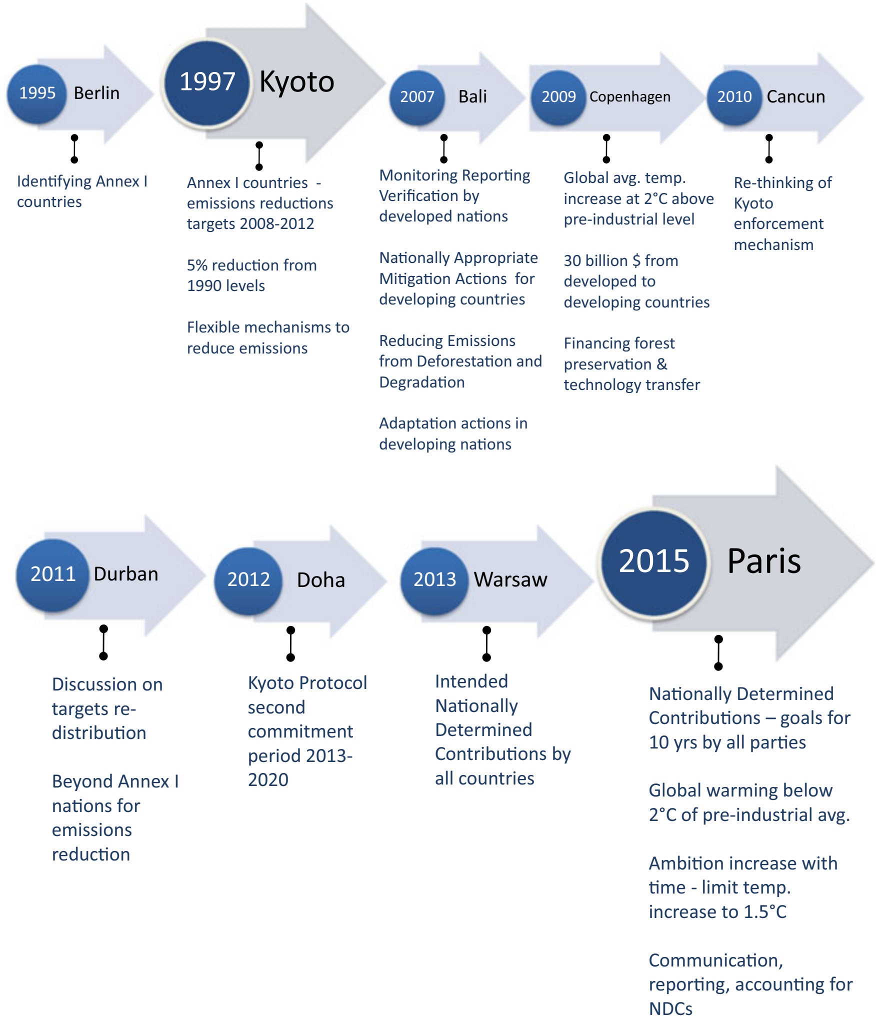

Fig. 5 Trajectory of international climate agreements

2 Influencing Factors

International cooperation on climate change has come a long way from since its inception to a post-Paris setting. The UNFCCC and its various agreements have successfully etched a climate change agenda on the global map and established an institutional architecture needed to drive collective action. In its over three decades of driving global climate cooperation, the UNFCCC has premised the key discussions on first, a scientific knowledge of where we are and second, setting goals for where we want to go. The decisions that have emerged at the various COPs have rested on these key fundamentals and shaped the trajectory of the climate architecture helmed by the United Nations.

At the same time, the decision making at the COPs, participation of the ratifying parties, the progress of climate goals and other aspects are influenced by various factors, which make the design and operation of the processes involved complex in nature. The evolution of the trajectory of international climate change agreements and the role that has been played by the UN and its institutions can be viewed in the light of these factors in order to understand the relevance and achievement.

2.1 Political Economy Imperatives

Global cooperation for climate change has political, social, and economic dimensions that operate between nations and within a nation and manifest in the form of disparities of resource distribution, political and economic power. The political context and economic imperatives influence a nation's decisions to support or opt-out of emissions reduction goals or restrain developing nations from engaging in voluntary emissions reductions (Stiglitz et al. 2001). Countries differ in their relationship with the climate challenge in various ways like their contribution to GHG emissions, degree of vulnerability to experiencing impacts (both in scale and immediacy), economic and political power to negotiate at COPs, and the scientific and technical capacity to work towards fulfilling targets and goals. The interaction and play of these various elements determine a party's national climate change-related priorities, allocation of responsibility for current and historic harm, and perceptions of climate change that prevail among its citizens (Running 2012; Atapattu and Gonzalez 2015).

The fundamental tenets adopted by the UNFCCC recognise the differences that exist in the present world politico-economic order. The convention enshrines the principle of "*common but differentiated responsibility*" established in its charter and carried it forward as a core premise into the historic Kyoto Protocol. It cannot be denied that the industrialised economies have been responsible for the bulk of GHG emissions, at a time when the developing economies still grappled with fulfilling basic development challenges. Nonetheless, the cooperation of the latter is essential for the success of international regulations on climate cooperation. The convention sought cognizance of this assertion as it moved progressively towards the Paris Agreement, which was then designed to make all parties (and not only the industrialised economies) accountable for reducing emissions, while it continued to set the "*principle of common but differentiated responsibility*" with "*respective capabilities*" and "*in the light of different national circumstances*" (UNFCCC 2015).

The differences in economic order particularly surface when making a transition to climate-friendly policy or a carbon neutral economy like adoption of cleaner technologies. The lack of such technological ability makes it difficult for governments in the developing countries to enact legislation governing emissions. Thus, climate agreements also evolved to make provisions for funding support to developing nations through various instruments, where funding is pooled from developed economies.

2.2 Decision Making Approach

From Kyoto to Paris, the UNFCCC witnessed strong multilateralism in the creation and endorsement of its protocols, agreements and frameworks. Its decision making process, however, by design, deployed a "top-down" approach. The overall goal setting is formulated through negotiations and deliberations where it is the representatives of national governments of the parties who participate. The levels of government further below, for instance the regional level and below, have traditionally not been the key determining participants at the main deliberations, though they may participate in various side events and specific discussions organised at the COPs.

The Paris Agreement marked a shift to a more "bottom-up" approach. Its structure and design are distinctive from the previous agreements, as it paved way for the respective parties to devise their own targets and included reliance on not just national, but also on regional and sub-national levels of governance, and non-state actors. The transition seen in the Paris Agreement demonstrates an evolution in the degree of centralised authority, and marks a shift to a more decentralised approach, at the same time, allowing for greater harmonisation of national policies (Galarraga et al. 2009; Stavins et al. 2014; Chan et al. 2018).

2.3 Data Necessity

The setting of quantifiable goals and targets like in the Kyoto Protocol and the Paris Agreement requires scientific data and information. The IPCC reports have played a significant role in supporting the UNFCCC with data and information that provides a base for overall goal setting. In this sense, the coordination and close working between the IPCC and UNFCCC has been marked with a great degree of success. What remains to be seen in equal measure, however, is the availability and use of data showing how the macro goals translate and trickle down into micro targets further down from the global and national levels.

Yet another grey area that calls for informed data is on the costs of climate action: costs of mitigation and the costs for bearing the impacts, that is, costs for building climate resilience and measures for adaptation. The degree and extent of these costs is required, firstly, to drive nations to meet targets, and secondly, to plan the future course of action. In the event of a lack of certain or indicative costs, the data needs to be generated, and a mechanism can be devised to include it in the reporting and accounting system. There is a need to measure the costs of emissions reduction with the costs of bearing the impacts, and it is important to gain benefits of emissions reductions at the lowest possible costs with a combination of elements like market-based instruments, integration of climate change in policy areas, technological innovation and diffusion (OECD 2007). The limitation in the above, coupled with an uncertainty over the evident benefits that will accrue and the long-distance time period of the benefits to be received, has led to slower global climate deeds.

2.4 Mitigation vs. Adaptation Focus

Mitigation and adaptation are like two sides of the climate coin and need to be addressed in equal light in order to deal with climate change. Yet, international climate policy has focused more on mitigation, while adaptation has been dealt with more broadly. From inception, the international climate environment has largely centered on mitigation, but slowly recognised the need for bringing attention to adaptation. Therefore, the COPs from Bali onwards initiated discussions and measures on adaptation. In the more immediate term, it is very critical to push for adaptation efforts, as climate impacts are already being felt in different parts of the globe causing much havoc.

Two elements ingrained in climate policy design and overall goal setting, illustrate the point further. First, the time frame reflected in climate policy goal setting is medium to long-range and is more aligned to mitigation, the results of which are visible only over a period of time. Whereas, in the short-range scenario, the immediate need is adaptation and building resilience. The NDCs of the Paris Agreement are primarily shaped as national mitigation targets and include adaptation as an additional measure. Second, the UNFCCC and its agreements have been based on a 'precautionary principle', more associated with mitigation rather than also being inclusive of a 'curative principle' that will correspond with adaptation and climate-related suffering.

Yet another dimension is the definition of parties that is premised on contribution to emissions more than on the basis of vulnerability to impacts of climate change. It is the greater vulnerability to climate risks and hazards that has motivated some nations to advocate strongly during climate negotiations. Many of these nations have come together in coalitions and associations to design adaptation strategies. If some nations are more at risk than others, it may be prudent to be more inclusive of the element of vulnerability when defining "Parties" of the convention.

3 Regional, Non-UN, Non-State Groups

Even as the UNFCCC remains a core platform, other institutions have emerged at different levels and varied in nature such that the institutional landscape of international cooperation on climate change, from the time of its inception, has become diverse. The push lent to the climate agenda by international agreements has led to a horizontal and vertical ripple effect, evident in the emergence of regional groups, and distinct non-UN and non-state groups, which are slowly becoming the on-ground torchbearers of climate action.

Regional Groups: The UNFCCC recognises the role of regional groups, and gives them observer or consultative status at its COPs; both UNDP and UNEP work closely with various regional groups. Examples of regional groups are: Forum of Global Associations of Regions (FOGAR), Network of Regional Governments for Sustainable Development (Nrg4sd), Association of European Border Regions (AEBR), Latin-American Organisation of Intermediate Governments (OLAGI), and Integration Zone of the Centre-West Region of Southern America (ZICOSUR). There are also examples of states or provinces of a participating nation, which have taken pro-active measures as a region and set targets beyond or over and above national targets. For instance, British Columbia in Canada aimed for a 33% reduction of 2007 GHG emissions levels by 2020 and 80% by 2050, New South Wales in Australia set out to reduce 60% emissions by 2050 and a reduction to 2000 levels by 2025. Being closer to ground reality, the regional groups can play a more influential role in implementing goals and actions and raising awareness among citizens (Galarraga et al. 2009, Chan et al. 2018; Stavins et al. 2014).

Non-UN Groups: Non-UN groups include groups like REDD + partnership, International Renewable Energy Agency (IRENA), and the Major Economies Forum on Energy and Climate Change (MEF). The REDD + partnership focuses on enhancing forest carbon stock through conservation and sustainable forest management, IRENA promotes development of renewable energy and the MEF is a discussion forum for for its members, who together account for 70% of global GHG emissions (Stavins et al. 2014).

Non-State Groups: Non-state groups are in the form of public–private partnerships (PPP), private sector governance initiatives, NGO transnational initiatives and sub-national trans-national initiatives. Public–private collaborations include the Renewable Energy and Energy Efficiency Partnership (REEEP), the Global Methane Initiative and the Global Superior Energy Performance Partnership. Private sector actors have also governed more directly by setting voluntary carbon disclosure or standards or supporting developing systems of accounting. NGO transnational initiatives include certification schemes for carbon offset like Gold Standard, or forestry credit schemes like Climate, Community and Biodiversity Alliance standard; while, the sub-national transnational initiatives include the International Council for Local Environmental Initiatives (ICLEI), a network of local governments for sustainability and C40 Cities Climate Leadership Group (Stavins et al. 2014; Chan et al. 2018) (see Fig. 6).

4 Conclusion

The landscape of international climate change agreements is complex, given its multi-sector and multi-scale intersections, and has seen a centrifugal flow in responsiveness to the climate emergency. It may be said that decisions and discussions of international agreements have served as a catalyst for a trickle-down to finance, investment, and policy change across multiple sectors, which in turn, is being seen into effect by a plethora of actors and institutions that have emerged across scales and geographies. The way forward calls for innovative measures for investment and climate finance, accelerating green technologies and practices, devising ways to change consumer

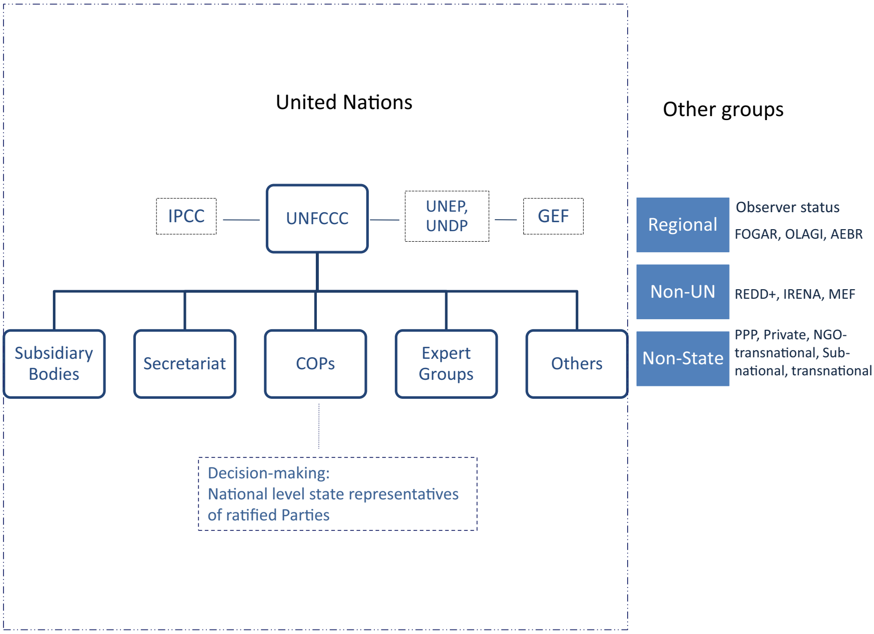

Fig. 6 Institutional architecture of global climate cooperation

behaviour to support green technologies and practices, encouraging efforts that have "co-benefits" and above all strengthening inclusion of climate policy across sectors; all of which will result with enhanced coordination to and from multiple scales and actors.

Today, we see that a new generation of climate activists have emerged across the globe to push the climate agenda harder and country discussions, goals are moving towards net-zero emissions and increasing levels of self-commitment by setting ambitious targets. Amidst this, progress towards targets remains a distant run, as collectively, nations lag behind. There is a pressing need to pull up systems for measurement. At the same time, a different approach in the present 'voluntary' liability system may bring greater compliance to achieve targets.

What is most critical in going forward and propelling further action is whether we a need to adopt a different haul and paradigm in which the international policy operates, to make it more incumbent and inevitable for nations to inch closer to targets with greater urgency. The current perspective in international climate change discourse is about "sharing a common burden" rather than about "maximizing benefits of preventing climate change damages" (Metz 2010). A change in perspective from the former to the latter can fuel the growing climate policy regime.

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Carbon Dioxide Capture and Sequestration to Achieve Paris Climate Targets

Pushp Bajaj and Saurabh Thakur

Abstract The Paris Climate Agreement, signed by over 190 countries at COP21 of the UNFCCC in 2015, set a unique precedent in the global fight against climate change. The signing parties agreed to limit global warming well below 2 °C, aiming for 1.5 °C, which poses a herculean task for the international community. Studies have shown that this target could only be achieved through drastic cuts in global greenhouse gas emissions and large-scale removal of excess carbon dioxide from the atmosphere. In this context, this chapter highlights the latest developments in the science and technology of carbon capture and storage techniques, including land-based and ocean-based techniques, bio-energy with carbon capture and storage (BECCS), and direct air capture (DAC), which would be critical in our efforts to mitigate climate change. The chapter also discusses the technological, financial, ethical, and socio-political challenges and limitations that would need to be addressed for large-scale deployment of carbon capture and storage technologies. As global carbon emissions continue to rise unabated, the need for carbon dioxide removal technologies will grow simultaneously. More research and development is needed to solve the outstanding problems and make these technologies safe, sustainable, and economically feasible for large-scale deployment.

Keywords Carbon dioxide capture · Carbon sequestration · Paris agreement · Negative emissions · BECCS · Direct air capture

1 Introduction

In 2015, the global average temperature rose 1 degree Celsius (°C) above pre-industrial levels (1850–1900 average) for the first time. Last year, 2020, tied with 2016 for the hottest year ever recorded at 1.25 °C above the 1850–1900 average (Carrington 2021). This marked an important milestone; the last time the planet was more than 1 °C warmer was during the last interglacial period around 1,20,000 years ago (NEEM Community Members 2013). While 1 °C may appear to be a small

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change, on average, it corresponds to a very different climate on planet Earth. This 1 °C rise in temperature has modified the hydrological cycle, the carbon cycle, and other natural cycles. The global mean sea level has increased by about 21–24 cm (cm) since 1880 (Lindsey 2020). Extreme weather events, such as heatwaves, droughts, extreme rainfall, cyclones, storm surges, etc., have become more common, more intense, and less predictable.

What is more worrisome is that the temperature rise is accelerating. With the increase of every fraction of degree, the impacts on the natural cycles grow larger and, in turn, the socio-economic impacts on human civilisations increase exponentially. This temperature rise is being fuelled primarily by the relentlessly rising greenhouse gases in the atmosphere primarily emitted by the burning of fossil fuels by humans (Mann et al. 2016; Hansen and Stone 2016; UCSUSA 2017). Among them, the most important greenhouse gas is carbon dioxide (CO_2) due to its long 'lifetime' in the atmosphere. Once emitted, CO_2 stays in the atmosphere for several hundreds to thousands of years before being removed by natural processes (Archer et al. 2009). In other words, planetary temperatures will continue to rise as long as we continue to emit CO_2 into the atmosphere and this warming will be irreversible on the order of hundreds to thousands of years considering the long lifetime of CO_2 in the atmosphere.

In this context, this chapter will highlight why CO_2 capture and storage are absolutely essential in humanity's efforts to mitigate climate change by bringing down the atmospheric CO_2 concentration to "safe levels". And how it can be achieved using a combination of nature-based and technological methods. Section 2 will outline the ambitious 2015 Paris Climate Agreement targets and how they can only be achieved with large-scale use of carbon dioxide removal (CDR) techniques in addition to drastic reductions in greenhouse gas emissions. The major CDR techniques that are currently being explored and implemented, albeit at small scales, by the international community, will be critically analysed in Sect. 3. Finally, Sect. 4 will discuss the ethical, political and economic challenges and discuss potential future pathways for successful large-scale deployment of CDR in order to accomplish the daunting task of restoring the climate to normalcy.

2 The Key to Achieving Paris Climate Targets

The Paris Climate Agreement, signed by over 190 countries in Paris at the 21st Conference of Parties (COP21) of the United Nations' Framework Convention on Climate Change (UNFCCC), is a unique and unprecedented international climate agreement. For the first time, almost all nations of the world came together and agreed that climate change poses a serious threat to global security and prosperity. The signatories of the agreement pledged to limit global warming well below 2 °C, aiming for 1.5 °C, in order to avoid some of the worst impacts. Following that, the United Nations' Intergovernmental Panel on Climate Change (IPCC) was tasked to quantify the physical and socio-economic impacts of climate change that will occur if the global average temperature rises by 2 and 1.5 °C above pre-industrial levels.

In 2018, the UN IPCC produced a comprehensive special report titled "Global Warming of 1.5 °C" with a detailed comparison between the impacts of 1.5 and 2 °C of global warming above pre-industrial levels (IPCC 2018). The report also outlined a science-based action plan to achieve the 1.5 °C target. One of the central conclusions of the report was that, in order to halt global warming below 2 °C the global annual carbon emissions must drop by 25% by the year 2030 relative to 2010 levels and further to net-zero by 2070. The emission cuts would have to be even more dramatic to stay below 1.5 °C, global annual carbon emissions must be reduced to nearly half of their 2010 value by 2030 and to net-zero by 2050. This represents a herculean task which would require an urgent and drastic transformation in almost all sectors of the global economy. Notably, some sectors of the economy such as the aviation and shipping sectors are particularly difficult to decarbonise because there are currently no alternative zero-carbon fuels for airplanes and large cargo ships.

This sobering conclusion has rightfully gained significant attention from academics, journalists, policy makers, and climate change activists. However, the less appreciated fact is that the report also found that all scenarios limiting global warming to 1.5 °C or 2 °C require the use of CDR on the order of 100–1000 giga tonnes of CO_2 ($GtCO_2$) over the twenty-first century (Rogelj et al. 2018). That is more than 2–20 times the current global annual CO_2 emissions. This is largely meant to offset emissions from sectors that cannot be easily decarbonised with current technologies as mentioned above. Moreover, the more we delay significant cuts in carbon emissions, the more we will have to rely on CDR technologies to make up the difference. According to a recent estimate by the International Energy Agency (IEA), currently there are 21 large-scale commercial CDR facilities around the world, almost half of them located in the United States, absorbing only up to 40 million tonnes of CO_2 ($MtCO_2$) each year (IEA 2020). Considering that the current, non-binding pledges made by most nations are grossly incompatible with the Paris targets, it would be wise to assume that CDR would become increasingly necessary in the coming decades.

3 Current Techniques to Carture and Store Cabron Dioxide

When it comes to carbon capture and sequestration, the natural systems are highly efficient at the task. On land, soils and terrestrial vegetation sequester large amounts of carbon from the atmosphere throughout their lifetimes. The oceans, too, absorb large quantities of carbon through a number of physical, chemical and biological processes. These natural "carbon-sinks" are critical components of the carbon cycle of the planet and regulate the atmospheric carbon dioxide levels which, in turn, regulates the climate. However, with rapid urbanisation and the growing impacts of climate change the natural carbon sinks are diminishing at an alarming rate while the anthropogenic carbon dioxide emissions are increasing. As long as this imbalance continues growing, the atmospheric carbon dioxide levels will continue increasing at accelerating rates and consequently the planetary temperature will continue rising.

Of course, the obvious way to counteract this imbalance would be to protect and conserve the natural carbon sinks and/or enhance their capacity to extract more carbon dioxide the atmosphere. So, for terrestrial systems this could be achieved through reforestation and afforestation, and restoration of soils for enhanced carbon storage. For marine systems, it would involve conservation of marine plants and forests starting from the microscopic phytoplankton colonies to other coastal ecosystems such as mangroves, seagrass, corals, etc. Additionally, scientists and engineers have developed artificial/ technological methods to supplement the natural processes to remove carbon dioxide directly from the atmosphere or capture it at the source (such as industrial exhausts) and prevent it from entering the atmosphere (National Research Council 2015). The captured carbon is then concentrated and disposed, either by storing it deep underground or in the ocean or by using it to produce other commercial products. Traditional Carbon Capture and Storage (CCS) (from industry, fossil-fuel power plants, etc.), sometimes also referred to as Carbon Capture Utilisation and Storage (CCUS), Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) are some examples of technological solutions. This section will provide an overview of some the most promising CDR techniques that are either being actively implemented currently or have the potential to be implemented at scale in the future.

3.1 Terrestrial Reforestation and Afforestation

The term Reforestation refers to restoration of forest on recently deforested land and Afforestation refers to forestation of previously unforested land or land that has been deforested for 50 years or more. Any climate change mitigation strategy is incomplete without a comprehensive plan for land-use and forestry. According to global models-based estimates, land-use and land-use change resulted in around 5.2 $GtCO_2$ emissions per year during the 2007–2016 period, accounting for around 13% of the global CO_2 emissions (IPCC 2019). These emissions are mainly driven by deforestation and land degradation and partly offset by reforestation/ afforestation and soil restoration. While preventing deforestation is critical to reduce global annual CO_2 emissions, carefully planned reforestation and afforestation activities could remove significant amounts of CO_2 from the atmosphere over long time scales resulting in "negative emissions".

However, there are a number of nuances that must be considered in order to maximise the CO_2 from afforestation and reforestation. Different forest ecosystems, such as the boreal, temperature and tropical forests, could have very different rates of net annual CO_2 uptake, ranging from 1.5 tCO_2/ha to 30 tCO_2/ha (IPCC 2019). It is important to note that this net uptake of CO_2 follows a bell-curve over time which reaches the maximum value in around three to four decades followed by a gradual decline. The timing of the maximum also depends on the specific type of the forest.

However, this natural profile could be disrupted by natural or man-made disasters such as forest fires, droughts or pest attacks, which are, ironically, becoming more frequent and extreme due to climate change.

Recent models-based estimates suggest that the upper limit of the carbon capture potential from reforestation and afforestation could be in the range of 1–7 $GtCO_2$ per year by 2050 (de Connick et al. 2018). Of course, to achieve the maximum potential we would have to address the implementation challenges related to land requirements, water and nutrient (fertiliser) requirements, governance and legal issues, etc. Cost estimates are significantly lower than other CDR techniques (discussed below) and there would likely be ecosystem-services related benefits if species-diversity is taken into account in reforestation and afforestation efforts. Arguably, there are some concerns regarding the reduced albedo of forest canopies that may lead to more warming and the fact that forests will, in general, become more vulnerable to climate-change-induced forest fires and pest attacks, as mentioned before. Therefore, there is a need for careful planning and identifying synergies with other climate change mitigation strategies in order to make the case for reforestation and afforestation stronger.

3.2 Ocean-Based Carbon Sequestration

In protecting humans from global heating, the oceans are silently playing a very crucial role. Oceans act as massive natural carbon sinks, absorbing excess CO_2 from the atmosphere through multiple mechanisms. Scientific estimates suggest that, since the beginning of the industrial revolution, oceans have absorbed nearly one-third of all anthropogenic carbon dioxide emissions (Gruber et al. 2019). Carbon is stored in the oceans in two main forms- organic and inorganic. At the air-ocean water interface, there is constant exchange of CO_2 between the air and ocean water. Some of it gets dissolved into the ocean water and forms a weak acid, called carbonic acid, this comprises the inorganic carbon. The organic carbon, on the other hand, is that which is captured by coastal and marine plants and micro-organisms primarily through the process of photosynthesis. Considering the vast expanse of the oceans there is huge potential for large quantities of CO_2 sequestration which has motivated scientists and experts to find ways to enhance these natural processes and increase the CO_2 storage capacity of the oceans.

One way to increase the surface absorption of ocean water is through a process called “ocean alkalinisation”. The idea is to distribute ground up rock material (consisting of calcium and silicon primarily) in the surface waters where, under the right temperature and chemical composition of the water, they combine with CO_2 to produce dissolved alkaline bicarbonates and carbonates over time. This method could, in principle, be used to sequester large quantities of carbon but it is limited by the logistical aspects involved in extracting and distributing the rock minerals. Some estimates suggest that the carbon capture potential could be in the range of 1–6 $GtCO_2$ per year, however, the estimates are preliminary due to limited studies on the subject and the wide-ranging parameters that determine the potential (Kohler et al. 2013; Hauck et al. 2016; Renforth and Henderson 2017).

Ocean fertilisation through added nutrients is another approach to enhance carbon fixation in the ocean. Phytoplankton are microscopic marine plants that live in the surface waters. Just as terrestrial plants do, they absorb carbon dioxide from the atmosphere and sunlight for photosynthesis and release oxygen in the process. They are, in fact, the primary oxygen producers on the planet, they produce over 80% of the oxygen that we breathe. Phytoplankton are produced in the oceans in what are called "blooms" under specific atmospheric conditions. Their growth also relies on dissolved nutrients in the water, such as iron, nitrogen and phosphorous, which are in low supply. Scientists believe that, we could, in principle, enhance the growth of phytoplankton species by artificially adding these nutrients to ocean water. This process is referred in the scientific literature as "ocean fertilisation" (Harrison 2017). However, this has only been tested in laboratory settings, no large-scale field experiments have been conducted yet. There are also some outstanding questions regarding the impact that enhanced fertilisation could have on the broader marine food-web and in turn the marine biodiversity (Williamson et al. 2012). Simply considering the vast area that the ocean covers, the potential for carbon sequestration through the surface is quite significant, with more research and experimentation it could become a strong candidate for large-scale carbon dioxide removal from the atmosphere.

3.3 Bio-Energy with Carbon Capture and Storage (BECCS)

BECCS corresponds to a hybrid, natural-technological methodology in which 'biomass' is first generated by growing energy-intensive crops and then consumed (by burning or chemical conversion) to produce energy in the form of heat, electricity, and/ or liquid or gas fuels; the CO_2 that is generated during the consumption process is captured and stored, completing the process of BECCS. This is considered to be a 'net-negative' emissions technique, since, when the crops grow they absorb CO_2 from the atmosphere via photosynthesis and then when the matured crops are burnt, the emitted CO_2 is captured and stored (generally underground), thereby resulting in a net reduction of atmospheric CO_2. Due to the wide range of applications of bioenergy and the potential for net negative emissions when combined with CCS, BECCS is by far the most widely studied CDR technique (Kemper 2015). It is also extensively incorporated in the Integrated Assessment Modelling (IAMs) studies that are used by the UN's IPCC to make projections for future climate change.

Most modelling scenarios that limit global warming below 1.5 and 2 °C consist some combination of Afforestation and Reforestation with BECCS. According to the 2018 IPCC Special Report on "Global Warming of 1.5 °C", median values of BECCS deployment is estimated to be around 3, 5 and 7 $GtCO_2$ per year in 2050, depending on whether the global average temperature rise stays below 1.5 °C, slightly overshoots 1.5 °C, or highly overshoots 1.5 °C. The rates ramp up to 6, 12 and 15 $GtCO_2$ per year in 2100 (Rogelj et al. 2018). It is important to understand that these are median deployment rates; there are some scenarios compatible with 1.5 °C of global warming which do not rely on BECCS, but instead use afforestation and reforestation for CDR or do not rely on any form of CDR but instead assume deep cuts in global carbon emissions in the short-term. Some of these hypothetical scenarios are likely only of academic value and do not represent practical real-world possibilities. As mentioned before, it is highly likely that we would need large-scale deployment of CDR technologies during the twenty-first century and BECCS would almost certainly be one of these technologies.

According to a 2013 study which considered switchgrass as the energy crop for BECCS, in order to remove 1 Peta gram of Carbon per year (PgC/yr) equivalent to 3.7 $GtCO_2$/yr, it would require 200 million hectares of land, 20 Terra gram per year (Tg/yr) of Nitrogen, and consume 4000 cubic kilometres per year (km^3/yr) of water (equal to current global water withdrawals for irrigation) (Smith and Torn 2013). Of course, these demanding land and resources requirements pose a major challenge for large-scale deployment of BECCS, particularly considering the ever-growing land requirement for food crops and feedstock for cattle to feed the growing population. Large-scale biomass plantations may have to replace existing forests and grasslands which would not only affect the biodiversity but also release the CO_2 stored in these forests when they are cleared. Additionally, if the biomass plantations adopt a monoculture practice that would be detrimental to the soil quality and reduce their natural capacity to store CO_2 and eventually lead to land degradation. Considering this, scientists are trying to explore better energy crops and/ or better practices that require less resources and may not compete with food crops (Kline et al. 2016).

Nonetheless, once the CO_2 has been captured and concentrated it needs to be stored away permanently in order to complete the carbon dioxide removal process. One popular option in this case is geological sequestration, which is to inject concentrated CO_2 deep underground in depleted hydrocarbon reservoirs or saline aquifers. Several studies in recent years have estimated the potential global geological CO_2 storage capacity, the estimates range from a few thousand $GtCO_2$ to tens of thousands of $GtCO_2$ (Benson et al. 2012; Dooley 2013). In comparison, the total anthropogenic carbon emissions to date are on the order of ~2000–2500 $GtCO_2$. So, in principle, there is enough capacity underground to sequester human-caused carbon emissions. There are, however, some challenges in implementation and potential side-effects that must be taken into account.

The current global CO_2 capture and storage capacity of large-scale facilities, including those that are in the development stages, is on the order of ~100 mega tonnes of CO_2 ($MtCO_2$) per year (Global CCS Institute 2020). There is a long way to go before we reach the scale that is necessary to achieve the Paris Climate targets, which would be on the order of ~ 10$GtCO_2$/year. The CO_2 captured has to be transported from the source (typically fossil-fuel or biomass-based power generation facility) to the sequestration facility in pressurized containers or through pipelines. There are also important considerations regarding the long-term integrity of the geological carbon sinks that must be considered. Some studies have shown that leakage of CO_2, depending on the characteristics of the reservoir, is possible, however, the probability decreases over time as the CO_2 is sequestered through secondary trapping mechanisms (GEA 2012). Studies also show that large amounts of injected CO_2 could increase the risk of seismic events (earthquakes) which in turn could destabilise the reservoir and lead to CO_2 leakage (National Research Council 2013; Gan and Frohlich 2013; Zoback and Gorelick 2012). There are some proposals of sequestering carbon dioxide under the ocean depths as well, at 1000 to 3000 m depth where it could be stored for hundreds to thousands of years before it returns to the atmosphere through natural ocean circulation (Rau 2011). However, there are a few unknowns in terms of the biological impacts, potential costs, and long-term efficacy of this approach, hence it has primarily been discussed at the academic level so far and not been demonstrated at scale yet. A lot more research is needed to identify practical solutions to the problems mentioned above in order to make BECCS an effective CDR option that can be deployed at large-scales (Stavrakas et al. 2018).

3.4 Direct Air Capture

Direct Air Capture (DAC) and Storage (DACS) is a relatively new and purely technological methodology that is being debated more and more in climate mitigation discussions. As the name suggests, it is a process in which CO_2 is captured literally out of thin air and concentrated before it is utilised in other processes or sequestered underground. The separation of CO_2 from air is typically carried out using chemical sorbents (amine- or hydroxide-based), which must then be regenerated to produce a stream of pure CO_2 (Sans-Perez et al. 2016). There is a very important difference between DACS and conventional CCS or BECCS which is that conventional CCS extracts carbon from a ‘point source’ such as an exhaust at a fossil-fuel power generation plant while in DACS CO_2 is captured from ambient air. A point source is, of course, much more concentrated in CO_2 than air which makes DACS a much more challenging task.

Since the CO_2 concentration is very low in air, the amount of work required to ‘capture’ it is significantly greater compared to conventional CCS or BECCS where the CO_2 concentrations are much higher (Wilcox et al. 2014, 2017). Therefore, DACS is more energy intensive, it requires at least 2 to 10 times the amount of energy required to capture CO_2 from point sources. Of course, the energy for operation must come from CO_2-free renewable sources in order to be optimal as a CDR technique. Another consequence of the low CO_2 concentration in air is that the absorption device must have a large cross-sectional area, in order to get the most exposure, and be very shallow, in order to avoid a pressure-drop. In comparison, a similar device for point-source capture is likely to be tall and thin. DACS facilities, therefore, tend to be much larger in size and require bigger land areas. Due to these reasons, the costs associated with DACS are prohibitively high in comparison to other CDR techniques and current estimates range widely (on the order of a few hundred US dollars per tonne of CO_2 to a thousand US dollars per tonne of CO_2) depending on the underlying assumptions and the type of air capture methodology considered (House et al. 2011; APS 2011; Mazzotti et al. 2013).

Finally, once the CO_2 is captured, it needs to be sequestered or utilised in some way, as is the case in BECCS described in Sect. 3.3. In this context, there is one advantage of DACS over BECCS which is that a DACS facility, in principle, does not have a site-specific limitation. In other words, a DACS facility can be installed with or close to a carbon sequestration or utilisation facility and minimise transportation costs. The DACS technology is at a very nascent stage of development with only small-scale experiments carried out to date. Before it could be implemented at a large-scale, carbon sequestration technologies would have to be well established and the energy-land requirements would have to be addressed. For DACS to make commercial sense, it would have to be supported by effective policies that incentivise negative carbon emissions even as the technology approaches optimal efficiency.

4 Current Challenges and Way Forward

As was also discussed in Section II, the Working Group three (WG3) of the IPCC AR5 as well as the IPCC SR15 presented an elaborate explanation for the need for the Negative Emissions Technology (NET). The achievement of both the 2 °C target as well as the aspirational target of 1.5 °C by 2050, according to nearly 900 mitigation scenarios generated through integrated assessment models (IAMs), will heavily rely on the use of NETs. As the remaining "carbon budget" continues to deplete at a fast pace, the debate on negative emissions, which is fraught with political and ethical concerns, has gained momentum in the face of accelerated pace of emissions (Hilaire et al. 2019; Rogelj et al. 2018; Quere et al. 2018; Fuhrman et al. 2019). Although the projected benefits of these technologies provide a hopeful picture, most of them have not moved beyond small-scale demonstrations on the ground to be viewed as cost-optimal alternatives. Several studies have argued that NETs cannot be viewed as panacea to overcome the political inertia which dominates our current responses to the problem of anthropogenic climate change (Anderson and Peters 2016). NETs cannot and should not be viewed as an insurance policy, but rather an unjust and high stakes gamble which is likely to raise a number of other concerns both moral and socio-economic in nature. In this climate of political and scientific uncertainty, it is important to flesh out these concerns which are likely to raise as large-scale deployment of NETs become feasible.

4.1 Ethical Concerns

Although the debate surrounding the NETs is fairly recent in its origins, but they are rooted in a longstanding discourse which began in the post-World War II period and posed the question regarding the role of modern technology in dealing with the social issues and environmental problems. At the birth of the environmental debates in the 1960s, the technological solution to the problems of ecology became a paramount concern as scientists, engineers, innovators and policymakers emerged as the lead actors in society. The technological fix was seen at the time as the logical solution to the problems, but it proved to be a short-sighted way of tackling the ecological issues, especially as their complexity of the challenge grew and several ethical concerns were raised with regards to the role of unfettered technological fixes in an unequal world. Much of the criticism focused upon the reductionistic nature of such solutions, wherein the rational decision-making approaches overlooked the key concerns that emerged from an ethical and socio-political standpoint. The primary concern with technology, from an ethical standpoint, was the asymmetry of power between the states, and inequity between individuals. This criticism has been extended to the debates surrounding the NETs as well, wherein it is viewed as myopic in its understanding the scope of the problem, which carries the risk of disempowering the marginalised voices and their concerns, all in the name of universal good.

In a 2012 study conducted to understand the divergent claims and opinions on the NETs, an ethical matrix of carbon capture and storage was created, wherein principles of justice and a set of actors, including the non-human actors, were selected to understand the diverse framings of justice in the context of carbon capture and storage. It particularly considered the divergent concerns of different actors, including the non-human actors were assessed to frame the problem (Boucher and Gough 2012). The study found that the ethical framing of negative emissions technologies will require a mapping of, “a global network of localised researchers, communicating regularly with each other to understand the relationship between different actors’ understandings of principles and the technology’s compliance with and deviation from them with sensitivity to the significant cultural and linguistic diversity that would be encountered.” CCS presents a more complex ethical problem than the other alternative of renewable energy and the reasons for this include- Firstly, the accrued benefits of the CCS are tied to its storage and the effects of the stored CO_2 persists for a long time. Secondly, the CCS technology carries the risk of extended dependence on fossil fuels rather than fuel a just and green transition. Thirdly, both its costs and benefits will be unevenly distributed, where the poorest people will be unevenly impacted by the transition. Finally, the detractors of the CCS point towards the intergenerational legacy of its impact, especially in terms of waste management, where strong parallels have been drawn with risks involved in nuclear waste management (Brown 2011).

Compared to CCS, BECCS is held up as a greener alternative which overcomes the limitation of storage. However, it raises a whole different set of problems and ethical complications such as, “the costs of low-carbon energy will ultimately have to be met by consumers with knock-on effects on pricing and fuel poverty” (Gough et al., Social and Ethical Dimension of BECCS 2018). Like CCS, BECCS carries the risk of promoting the business-as-usual rates of fossil fuel consumption and hinder the growth and transition in poorer countries, who may lose land and resources at the altar of unchecked consumption in the developed world (Gough et al. 2018). Bioenergy production at scale will require large scale deployment of land and other resources to meet the carbon sequestration demands, which carries the risk of creating a food-water-energy nexus, especially in poorer countries where technologies like BECCS will compete with agricultural lands for meeting such demands (Kato and Yamagata

2014). The large-scale deployment of BECCS could endanger, "terrestrial species losses equivalent to, at least, a 2.8 °C temperature rise, leading to difficult trade-offs between biodiversity loss and temperature rise" (Anderson and Peters 2016).

The carbon sequestration technology also becomes difficult to implement from a procedural justice point of view (Ambrose and Arnaud 2005). While a business-as-usual scenario will raise legitimate concerns and claims from countries and communities who are facing the risk of extinction, but on the other hand a hard push for the such technologies could promote extractivist activities, particularly coal, and add to the vicious circle of poverty in many parts of the world (McLaren 2012). Unlike the nuclear power discourse, where level of public awareness and emotiveness is high, CCS and other similar technologies have not generated widespread public debates. Therefore, the debate on the ethics and public debate regarding the NETs has ranged from 'prudent pessimism' to unshaken optimism in technological solutions at large. Yet another criticism of the NETs emerges from the underlying assumptions about the reversibility of the problem and management of Nature through technology. This has been criticised as a case of hubris, where political and ethical solutions to the problem are sidestepped in the name of effectiveness. While it is true that NETs are not the pure cases of manipulation of Nature, such as the solar radiation management (SRM), but it is equally true that, "achieving the more stringent 1.5 °C target requires between 400–1000 $GtCO_2$ to be removed from the atmosphere via NETs. At current rates, utilizing BECCS or DAC to achieve this would imply storing 10–25 years of global CO_2 emissions under the Earth's crust. There are great dangers in overestimating our ability to do this justly, safely or effectively" (Lenzi 2018).

4.2 Political Economy of Carbon Sequestration

If the negative emissions technologies grow over the next a few decades, it will be driven by two contrasting forces- firstly, the economies of scale will be a critical factor in achieving any mass scale production and reducing cost of production over time. Secondly, as is case with all technological shifts, there will be a set of losers and winners in this transition. Resource scarcity is one of the central concerns that are likely to emerge in developing and poor countries where several socio-economic factors are critically linked with the climate policy. It is important to understand both these factors, in order to predict the fate of negative emissions technologies.

4.2.1 The Problem of Scale

A 2014 study by Mercator Institute found that an annual average of 6 billion tonnes of atmospheric CO_2 removal by the year 2050 would require a scale up rate of close to 60%. This figure is far lower than the one the IPCC AR5 of 2014 suggests between the range of eight and twelve billion tonnes. If the carbon removal technologies have to emerge as an alternative, they require a rapid scaling up of operations to be commercially viable and politically feasible. A key strategy to meet this target would require heavy investments in research and innovation, which, in this context, includes supply-side research and development of technologies and a demand side uptake, which is subject to greater public acceptance of such technologies. Most NETs are currently in nascent stages of production, often limited to small scale experimentation. The projected levels of carbon dioxide removal and storage through 'sinks' varies from 100 to 1000 $GtCO_2$, depending on the how well the Paris pathways to zero net emissions are met through traditional, biological and geochemical processes over the next decades (Geden 2019).

Apart from the scale of economic investments, one key factor that will drive the innovation process is the political will to engage in the process. Artificial sinks are currently viewed as an additional option which can enhance the existing sink capacity that is available in the form of the natural ecosystems like tropical forests, peatlands and oceans (Peck et al. 2010; Ma et al. 2012; Nabuurs et al. 2013; Pan et al. 2011). The rapid decline of the natural equilibrium of ecosystems around the globe is leading to a disruption in the carbon cycle and increased accumulation of carbon in marine and terrestrial carbon sinks, disrupting the critical carbon budget estimates. The terrestrial sinks and oceans removed nearly 32.6 and 25.3% of fossil fuel based industrial emissions, respectively, in the brief period of 2007 to 2017 (Kennan and Williams 2018; Le Quere et al. 2018; Penuelas et al. 2017). In an extensive study of Peruvian Amazon, one of the largest natural existing sinks in the world, found that, much like the loss of peatlands in Siberia, South-East Asia and Canada, these peatland ecosystems are losing peat carbon to the atmosphere at a rapid pace due to external pressures such forest fires, intensive agriculture, and deforestation, which puts them at a risk of transforming into carbon sources rather than sinks (Wang et al. 2018).

Therefore, as the stresses on natural ecosystems increase, an important factor in scaling up carbon dioxide removal operations will be pace of innovation and their removal efficacy. A number of recent studies have yielded the results that favour a joint implementation of different kinds of technologies to maximise the negative emissions potential (Chen and Tavoni 2013; Marcucci et al. 2017). NETs technologies pose a different scaling up challenge, wherein BECCS will require massive upscaling on the ground and wider resource mobilisation, both of which are currently on short supply due to legislative and legal factors (Kemper 2015). In the case of Direct Air Capture with Carbon Storage (DACCS), the primary challenge remains the mass manufacturing. In the absence of large-scale demonstration, both feasibility and investment come into question for new technologies. Therefore, in order to attract investments, challenges related to feedstock availability, transportation, and system integration will have to be addressed on the supply side. The demand-side will require a greater emphasis on the construction of demonstration plants which can overcome the investor anxieties in a niche market that is both volatile and riddled with uncertainties due to factors like climate change policies (Iyer et al. 2015; Gough and Upham 2011).

In a recent survey conducted on the topic of socio-political mobilisation for the NETs, it was found that while BECCS feature extensively in the IAM projections, there is very little policy attention given to this topic, especially compared to nuclear power, thus raising concerns about their short-term uptake and feasibility (Fridahl 2017). The survey further found that, "if political, industrial, and public priorities result in preconditions for BECCS that disfavour deployment, then allowing an overshoot in pathways to limit temperature increase to well below 2 °C will have to rely either on other CO_2-removal technologies or on relatively cheap but unproven and potentially dangerous solar radiation management technologies." Recent studies have argued that full decarbonisation within a single generation is critical in order to meet the 1.5° target in the Paris Agreement. It is argued that an estimated 10–20 Gt CO_2 will have to be removed annually, which adds up to staggering 444–1000 Gt CO_2 removal by the year 2100 (Boysen et al. 2017). Such a massive scale of operation makes NETs virtually unavoidable for stakeholders, although such an expansion remains unprecedented in history. A peculiar trend is anticipated from a rapid and massive scaling up operations wherein, "costs would initially fall as the technology matures, and rise again as the resource scarcity of biomass (and to some extent storage) kicked in… Classical mitigation costs are expected to increase continuously from current levels as 'low-hanging fruit' are depleted and given the necessary increase in ambition compared to current mitigation action" (Honegger and Reiner, The political economy of negative emissions technologies: consequences for international policy design 2018). In their 2011 study of climate mitigation options, Gough and Upham (2011) favoured a smaller scale CCS or BECCS innovation as an exaggerated scale will eventually run into issues such as accessible infrastructure, resource scarcity. Their study further argued that bioenergy potential should not be projected extensively, given the lack of data on, "the cost of connecting bio-processing (combustion, gasification or other) infrastructure with CO_2 storage sites."

The uptake of new technology will, therefore, depend on overcoming the key constraints in the path to maturation of NETs, which includes the absence of capital, lack of political will, the near absent public demand and teething issues such as the free rider problem in the sector which inhibit innovation. This failure to grow is often described as a 'valley of death' problem, wherein new start-ups, and new technologies often fail to demonstrate their reliability at scale, which deters financial investors and results in such technologies never reaching the commercial markets where could expand (Nemet et al. 2018; Ford 2007).

4.2.2 The Resource Scarcity Question

While the NETs offer a critical pathway to the Paris Agreement targets, they will run up against a number of ecosystem-based constraints which includes the emerging food-water-energy nexus, massive changes in land use change (LUC) across the world, governance of artificial carbon sinks and anthropogenic climate change. Therefore, the technological transition cannot merely be seen as a technical transition; rather they have to be understood in the broader socio-technical landscape, where the impact of transition of socio-economic lives as well as planetary boundaries will be enormous (Creutzig et al. 2015; IPCC 2019). BECCS offers great prospects in meeting the Paris targets, their implications for a broad range of issues such as LUC, food security, energy security, water security, socio-political systems are relatively under researched (Fuhrman et al. 2020). It is an important aspect of the transition that NETs are attempting to bring about and highlight the often-neglected regional scale of these technologies. While the economic thinking and IAM projections are more focused on upscaling, a resource constraint on regional scale will pose a parallel, but equally vexing challenge for states and policymakers (Tian et al. 2016; Fuss et al. 2014; Zilberman 2015). The IAM projections which are highlighted in the IPCC AR5 rest on the assumptions based on perfect knowledge of yet unseen technologies and their cost-optimisation. One important consequence of this method is that it gives less weightage to future expenditure, in comparison with the present-day costs, thereby creating an impression that delay in action is a favourable strategy in the short run (Brack and King 2020; Bednar, Obersteiner and Wagner 2019).

Bioenergy is currently the source of nearly 10% of global energy supply, especially in the poor and developing countries, where people depend on these sources for daily needs like household cooking. These sources of bioenergy, therefore, cannot be shifted towards BECCS without accommodating for the needs of the poorest populations around the world (see Fig. 4.1). One of the major positives for the transition towards NETs relates to their potential to reduce dependency on fossil fuels. This claim, however, remains subject to both scrutiny and criticism. A 2018 study on the energy balance of BECCS highlighted that BECCS energy output will remain lower than the projected rates and returns will vary sharply on a case-to-case basis (Fajardy and Mac Dowell 2018). The study further observed that, "biomass conversion and CCS, followed by transport (road), drying, and farming (including inputs) represented over 80% of the energy losses for high moisture and low yield biomass such as willow pellets. Power plant efficiency, fuel efficiency for transport, transport

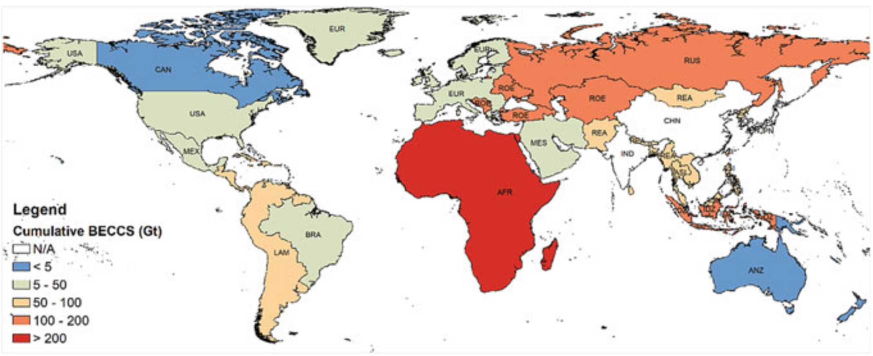

Fig. 4.1 Cumulative CO2 removal from BECCS under 1.5 °C policy with BECCS. 84% of BECCS deployment occurs in developing nations, with 26% alone in Africa. *Source* Fajardy, M., Morris, J., Gurgel, A., Herzog, H., Mac Dowell, N. and Paltsev, S., 2020. The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 C or 2 C world

distance, moisture content, drying method, as well as yield were thus identified as key parameters that need to be carefully controlled to maximise BECCS net electricity balance." As a way forward, the emphasis should be to disincentivise the usage of fossil fuels and invest in scaling up of operations to build reliable storage of CO_2 to meet the net-zero targets.

Yet another concern regarding the feasibility of such projects relates to their impact on natural resources and their local management. Water is a key point of concern in this regard as NETs projects are likely to lead to an increase in the water usage, which will be diverted towards the irrigation of bioenergy cultivation at a mass scale. Such large-scale shifts in the cropping patterns and potential rise in demand for biofuel crops will lead to higher stress on water tables, degradation of freshwater bodies and loss of biodiversity. In the context of climate change induced stresses, such diversions of key resources of survival will make any NETs project politically and socially unviable, especially in resource stressed regions of the world (Smith et al. 2016; Burns and Nicholson 2017; Gough and Mander 2019; Forster et al. 2020). The 2018 Royal Society report on Greenhouse Gas removal warns about the unintended consequences of the NETs, where, "indirect land-use change can involve spatial leakage—efforts to increase or protect forests in one location, without measures to meet demand for crops or ranching for meat, may push up crop and meat prices, increasing deforestation in another location." (The Royal Society 2018) A 2014 study on the future land-use scenario found that it would take a ten-fold increase in the yield of first-generation bioenergy crops like maize, sugarcane and rapeseed before 2055, thereby raising the demand for nutrient inputs, water, high fertiliser input. In addition to the increased cost of input and higher land use change, BECCS also carries the potential of increased nitrous oxide release into the atmosphere, thereby creating a new set of challenges (Kato and Yamagata 2014; Crutzen et al. 2016).

It is important to understand both the planetary scale impact of NETs as well as their regional, localised impacts, in order to make the right trade-offs. The deployment of CDR technology is projected to rise as the rates of carbon emissions rise, therefore, it has to be subjected to greater scientific scrutiny and socio-political analysis. The challenge for the policymakers will be to find the right equilibrium and appropriate scale for employing such technologies so as to yield their intended benefits.

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Carbon Credit and Climate Change Nexus

Jasmeet Singh Bajaj

Abstract This chapter reports the evolution of different approaches to tackle the problem of climate change and how carbon credits have provided a boost to address some of the associated glaring issues. The quantifiable approach toward measuring and mitigating the climate change impact is also captured. The chapter also provides analysis of key drivers to push the carbon credit mechanism. Under the Paris Agreement, the ambitious targets to retain global warming below 2 °C and attain an equilibrium of emissions needs a significant investment which is perceived as a major problem. The carbon market linkages are considered an important tool to contribute to the solution. The past experience of putting a price on carbon in different regions/countries and its impact toward adoption of technologies during last two decades is also captured. The information is encapsulated as case studies of various emission trading systems and carbon tax implementations across countries. Carbon credit has a great significance of in the current context of international climate change negotiations under the Paris Agreement. The future uncertainties and threats paving the path for voluntary carbon market is also explained at length. The positive outlook and thrust toward capturing the real impact within carbon credit is something under development. Post 2020, it is expected that precise quantified approach will be increasingly established to explain carbon credit node with climate change.

Keywords Carbon credits · Climate change · Paris agreement · Global emissions · Climate action · Climate finance

Abbreviations

AAUs	Assigned Amount Units
BAU	Business As Usual
CCBA	Climate, Community and Biodiversity Alliance

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CDM	Clean Development Mechanism
CERs	Certified Emission Reductions
COP	Conference of Parties
CORSIA	Carbon Offset and Reduction Scheme for International Aviation
EEA	European Economic Area
EIT	Economies in Transition
ERUs	Emission Reduction Units
EU	European Union
EU ETS	European Union Emission Trading System
GHG	Green House Gases
ICAO	International Civil Aviation Organization
IPCC	Inter-governmental Panel of Climate Change
KETS	Korean Emission Trading Scheme
ITMO	Internationally Transferred Mitigation Outcomes
NDC	Nationally Determined Contributions
NZ ETS	New Zealand Emission Trading Scheme
OECD	Organisation for Economic Co-operation and Development
SDG	Sustainable Development Goals
SDM	Sustainable Development Mechanism
Swiss ETS	Switzerland Emission Trading System
UNFCCC	United Nation Framework Convention on Climate Change
VCS	Verified Carbon Standard

1 Introduction

COVID-19 crisis has shocked the world, and all the countries are facing its brunt irrespective of their socio-economic background. The awful scenario of the world economy and the number of tragic deaths has shaken the growth and development pathways for many nations. The current pandemic cannot be compared with anything else. Still, if corrective measurements are not taken in time, the other crisis such as that of climate change that is being created could be worse than the current pandemic.

The average temperature of the earth's surface has already amplified by 1.7 degrees Fahrenheit since 1880 (Gillis 2017), which is roughly equal to 400,000 Hiroshima atomic bombs exploding across the planet every single day. The development of the UNFCCC, which came into force in 1994, established the stage for solving the problem of climate change.[1] The international negotiation arena between various nations also started in 1995,[2] over 25.[3] climate conferences have been conducted, known as COP.

[1] https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change.

[2] https://unfccc.int/resource/docs/cop1/07a01.pdf.

[3] https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop

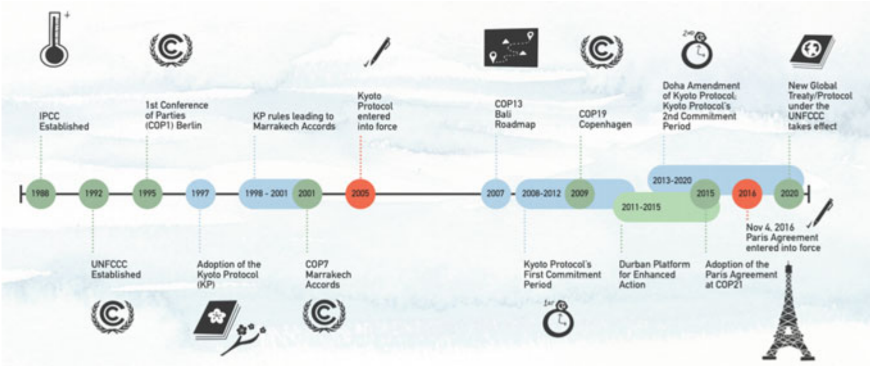

Fig. 1 Milestone of International Climate Change Negotiation Events. Reference—Illustration by Desiree Llanos Dee, Forest Foundation Philippines and Parabukas (2019)

The annual COP is an important event to discuss and evaluate the progress made globally to address climate change issues. From COP1 to COP25, several milestones have been achieved, including target setting and evolution of market mechanism. The below-mentioned timeline of annual COP meetings reflects the significant indicators, tools, and rules designed and implemented by the world to combat the climate change impacts.

The IPCC was established in 1988[4] to collate the data of GHG emissions and analyze its impacts to design the mitigation and adaptation tools. IPCC's primary focus was to intensify scientific research and create a knowledge bank for different countries to take necessary action. The report published by IPCC[5] in 1990 emphasized that climate change is real, and its distressing impacts on livable habitations are evident.

2 COP3—Kyoto Protocol

The preliminary decision in the history of climate change negotiation was to adopt the Kyoto treaty in 1997 at Kyoto, Japan. One hundred ninety-two countries later ratified the treaty[6] to check on six gases' concentration level (CO_2, CH_4, N_2O, HFC, PFC, SF_6). The targets were set for Annex I countries (those were a member of the OECD in 1992 including countries in EIT) to reduce total GHG emissions by at least 5% regarding the base emission level of 1990. "*The Kyoto Protocol was the first international piece of law that tried to articulate an idea of carbon rights and creating a market*" by Martijn.

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[4] https://www.ipcc.ch/about/.

[5] https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/.

[6] https://unfccc.int/process/the-kyoto-protocol/status-of-ratification.

Wilder. The development of the international carbon market is considered as one such tool to implement these mechanisms. To achieve the respective targets of obligated countries (Annex I), the Kyoto Protocol launched three mechanisms (Fig. 1).

Joint Implementation[7]
Under article 6 of the Kyoto Protocol, the emission reduction or emission removal project can be developed within Annex I countries. Surplus units of emission reduction called ERUs can be transferred from one country to another to meet their targets committed under the Kyoto Protocol.

Clean Development Mechanism[8]
Under article 12 of the Kyoto Protocol, the CDM gives Annex I countries the flexibility to take up emission reduction project activity in a developing country where the cost of reducing the GHG emission is significantly lower. The unit of emission reduction under this mechanism is known as CERs.

Emission Trading[9]

Under article 17 of the Kyoto Protocol, the countries falling under Annex B list may participate in emission trading to fulfil their commitments. The limits are assigned for emission reduction by AAUs. Emission trading allows those who have spare units to sell.

The Kyoto Protocol was adopted in 1997, but it took eight years for all the parties to bring the Kyoto Protocol into force in 2005. The regulated or 'compliance' markets were enforced under climate policies for countries to meet binding emission reduction targets set by governmental agencies (Paterson 2011). In 2008, the first commitment period of the Kyoto Protocol was started and concluded in 2012. The second term of the commitment period began from 2013 to 2020 at COP18, which lead to the Doha Amendment.[10]

3 Evolution of Carbon Market

As mentioned in the introduction, the idea of a carbon market initiated under Kyoto protocol evolved further by entering into the Paris Agreement. The carbon market currency was CO_2, wherein 1 tonne of CO_2 is equivalent to one credit unit traded in the market. During evolution, the market of carbon credit divided into compliance and voluntary markets. The compliance carbon markets focus on national governments' policy tools to keep a check and regulate the emission within a particular country's boundaries. On the other hand, the voluntary market got the traction to

[7] https://unfccc.int/process/the-kyoto-protocol/mechanisms/joint-implementation.

[8] https://cdm.unfccc.int/.

[9] https://unfccc.int/process/the-kyoto-protocol/mechanisms/emissions-trading.

[10] https://unfccc.int/process/the-kyoto-protocol/the-doha-amendment.

assess carbon emissions' quality with other sustainable development parameters like poverty, livelihood, gender, etc.

The key features of carbon credit needs to be put in a separate box on the left side in parallel to the first paragraph of chapter "evolution of carbon market".

- Additional
- Real
- Measurable
- Permanent
- Independent
- Unique

The compliance market represents a significant share of carbon credit transactions. The key stakeholders are companies and governments that by law should keep a check of their GHG emissions. This global compliance carbon market was also further linked with the national carbon reduction regimes by many countries. It resulted in the inception of cap and trade, carbon tax and carbon pricing program. As on 1 August 2020, 64 carbon pricing initiatives were either implemented or scheduled for implementation. The overall reach of these initiatives covers 46 national and 35 subnational jurisdictions. (World Bank 2020) (Figs. 2 and 3).

The carbon pricing initiatives are integrated with offsetting and carbon credit mechanism. However, there are special conditions put in by various initiatives which either boost or reduce the international demand for carbon credits under the Kyoto mechanism for some sectors and geographies. The primary stakeholder of compliance markets is national governments which drive the mechanism, as developing countries were exempted from the compliance mechanism (Shishlov et al. 2016). Besides the compliance demand, it has been observed that some groups are comprising of the private sector, public sector participation in the carbon market

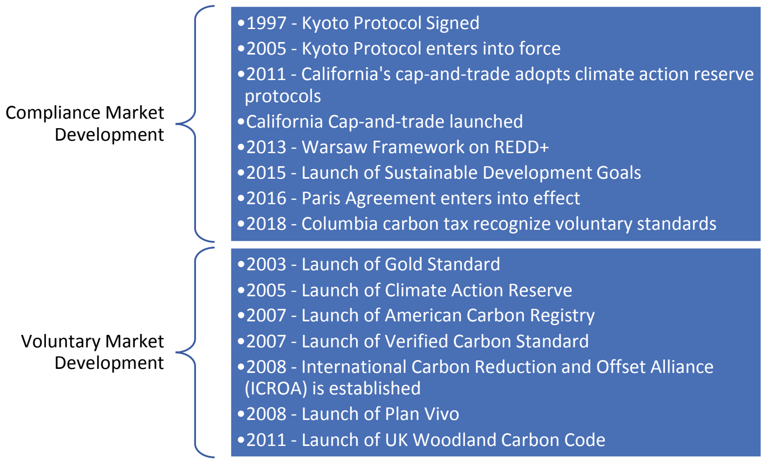

Fig. 2 Carbon market development: compliance and voluntary market, author explanation

voluntarily. Various voluntary mechanisms and standards have been formulated worldwide to meet such voluntary demand that is more customized and critical to carbon credits' specific fundamentals. The voluntary carbon market's governance is seen shifting toward the global targets to align itself with a scenario of 1.5 °C. (Michaelowa et al. 2019).

The popularity of voluntary carbon credits has increased in the last ten years. Several voluntary carbon standards have been established over the years; however, the gold standard remains the most available and accepted voluntary standard under quality certification. In total, the gold standard has implemented 800 + projects that are spread over 65 countries. Almost 117 million tonnes of CO_2e issued under the gold standard, out of which approximately 15% credits were issued in 2019 itself (Gold Standard 2020). The voluntary carbon market also provides more value to projects in terms of sustainable development as the special certification provision quantifies the impact of SDG 3, 5, and 6. The future of voluntary carbon market looks very promising, specific about gold standard as there is a pipeline of 2000 + projects which reflect the potential of 170 million tonnes of CO_2 per year, three times the annual emission of Switzerland (Gold Standard 2020).

4 Climate Action—Paris Agreement

After the Kyoto Protocol, almost all the nations are in consensus to take full ownership of limiting the global emission up to 1.5°. The Paris Agreement (United Nations, 2015) provides a pathway for developed nations to assist developing nations in their

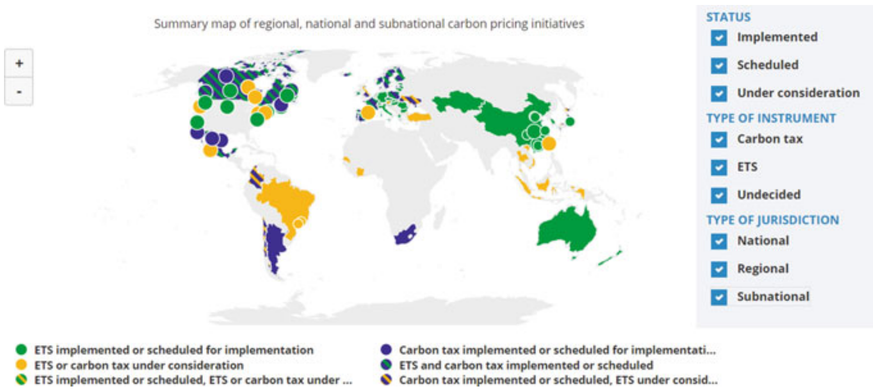

Fig. 3 Global landscape of carbon pricing. Reference: World Bank, Carbon Pricing Dashboard, Aug 2020

climate mitigation and adaptation efforts. It creates a framework for transparent monitoring, reporting, and ratcheting up of countries' individual and collective climate goals (Denchak 2018).

The Paris Agreement framework builds up a bottom-up approach wherein all the nations determine and commit their national commitments for emission reduction. However, there is still an unsolved puzzle for financing the NDC for developing and least developing countries. Unlike the Kyoto Protocol, the financing obligations are limited to developed nations, whereas under the Paris Agreement, any country, in theory, become the buyer and seller of emission reductions. There is a provision of bilateral cooperation under the agreement in Article 6. The three modalities for cooperation between the parties under Article 6 are:

- Article 6.2
- The bilateral cooperation will be formed for transferring and accounting of ITMOs. There are challenges related to the corresponding adjustment to design implementation modalities.
- Article 6.4
- A market-based approach to implementing an existing compliance market mechanism under the supervision of the UNFCCC Secretariat. A Supervisory Body will govern the mechanism, and in its activity cycle, it shares many similarities with the CDM.
- Article 6.8
- This is expected to be a federative instrument to augment the synergies and promote the implementation of approaches that do not involve the transfer of emission credits. There is a need to bring further clarity on the processes.

4.1 Fundamental Difference Between Kyoto Protocol to Paris Agreement

The whole world is waiting for the Paris Agreement's rulebook to be adopted to avoid further delay in combating climate change. The carbon credit mechanism played an essential role during the Kyoto Protocol and was an integral component of the Paris agreement. Though there are some fundamental differences like:

- *Stakeholder–Action*: Under the Kyoto period all the climate action was focused on Annex 1 countries where developed nation achieves the target, whereas now in the Paris Agreement, all the countries have made a commitment to take necessary action at national and international level.
- *Government and Non-state actors*: The Kyoto period were only focused on government action, whereas in the Paris Agreement, the inclusion of other non-state actors has happened, especially the private sector.

- *Science behind the Target:* The threshold limit was not set by climate science during the Kyoto period, the overall thrust was given to reduce the emissions. Under the Paris agreement, science-based targets have been formulated to define ambition.
- *Mitigation and Adaptation*: The climate mitigation scope was at the center during the Kyoto period, and electricity and industry emissions were perceived as significant carbon emissions drivers. The Paris agreement expanded the lens toward adaptation and other sectors like land use, agriculture, and forestry, that are also substantial contributors to global emissions.

5 Need for Carbon Credits to Address Climate Change

Several debates are going on concerning the Paris Agreement to arrive at a global consensus for establishing a market mechanism. About IPCC report, countries need to work out a plan for a 1.5° scenario. Though the target in terms of emission reduction is clear, there are still pending issues for forming a market approach, and carbon credits play an essential role in addressing those points. In the global climate action plan, the carbon credits will support in:

- *Ambition Gap*: It is clear from the countries' commitment that current pledges will not meet the 1.5 °C for which there is a need to raise the ambition and more market-based mechanism is required to bridge the knowledge gap. The carbon markets are an essential tool to fulfil the gap.
- *Finance Gap*: The targets of renewable energy need trillions, and there is a need to have private sector engagement through the market mechanism. The carbon credit financial tool is the only operational instrument wherein there is a high potential to accelerate private sector engagement.
- *Time Gap*: The carbon credit provides an opportunity to act immediately without further delay to implement. There is no time left to design new programmes, it is easy to customize the carbon market's current mechanism, and quick action can be taken.
- *Scope 3 Emissions*: The carbon credit is not the ultimate tool to address climate change. In order to reduce emissions as much as possible, operational and technological efficiency should first be implemented. However, scope three emissions are always considered challenging to reduce, where carbon credit can play an important role (Gold Standard 2018).
- *Carbon Price*: The carbon credit mechanism able to conceive a price to put on emission. The carbon credits are not allowing carbon pollution to be free. The markets do not exist or no rules on emission reduction—this helps align responsibility with climate impact.
- *Verified Impact*: The processes are in place to independently verify the emission as per the international standards. Different carbon standards cross-check the parameter of climate science behind each unit of emission reduction.

6 Global Emissions and Carbon Credit

In 2018, the world's total emissions stood at 33,513.3 million tonnes of CO_2, out of which a 40% addition happened beyond 1990, after the establishment of the IPCC (Frumhoff et al. 2015). The spread of the total world emissions is uneven for the sectors and geographies. During 2000–2018, more than 80% of total emission in the world came from three sectors only, i.e., Electricity and Heat production, Industry, and Transport (Figs. 4 and 5).

The representation of total emission by countries depends on their economy and the pace of their development. On average, 48% of the world's total emissions are only represented by four countries, i.e., Brazil, China, India, and the United States.

The above two graphs indicate the specific geographies and sectors that create maximum impact on addressing climate change. This chapter has analyzed the carbon

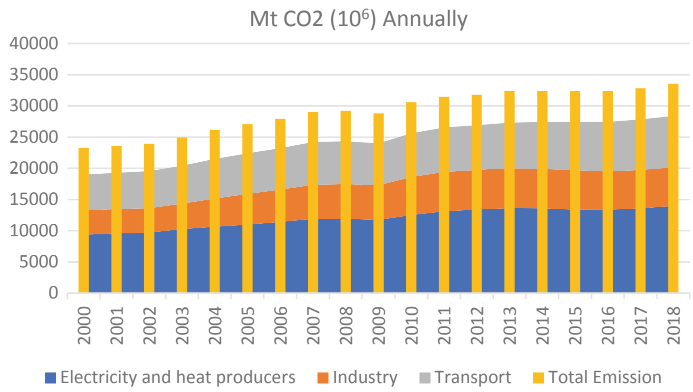

Fig. 4 Major global emission by sources, Reference—IEA 2020

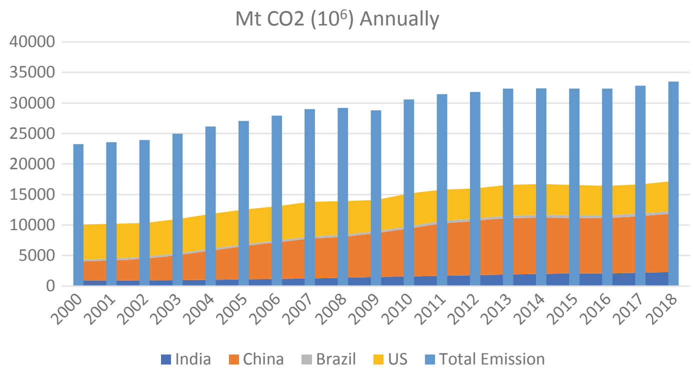

Fig. 5 Major global emissions by countries, Reference—IEA 2020

credit impact on particular sectors like Electricity and Heat production, Industries within the selected geographies of China, Brazil, India, and the United States.

6.1 Impact of Carbon Credit on Global Emissions

There are multiple co-relations between trading carbon credits and reducing emissions at the national and international levels. Here, carbon credits' impact is analyzed on the carbon intensity of industrial consumption in different regions. The base level of 2005 emissions is compared with 2018.

6.1.1 Brazil Carbon Emission and Reduction (2005–2018)

Brazil has the largest economy in South America and stands as the world's sixth largest GHG emissions contributor. It is a fascinating country in carbon emissions because the largest emission source is land-use change, a debatable topic. The analysis of the actual impact is yet to gain the confidence of market players. Unlike other countries, the delta, in per capita emissions is higher in production and consumption, whereas the GDP per capita is comparatively lower (Carbon Brief 2019).

The total emissions generated by Brazil's primary sources are compared with the project developed under the carbon credit mechanism with similar timelines. The carbon credits project demonstrates the contribution in reducing the national emissions by 10.43 and 20.51% in Industrial and Electricity and Heat Produce sectors, respectively (IEA 2020, UNEP DTU 2020) (Fig. 6).

In Brazil, the major acceleration in carbon emissions was due to increased oil consumption primarily for electricity and heat production. A clear inference can be drawn that carbon credit projects have supported the national emissions in reducing the carbon emissions by 20% (Tables 1 and 2).

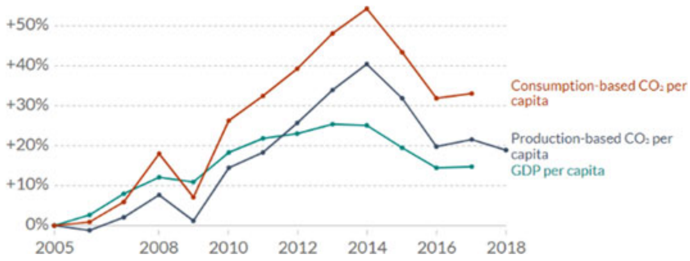

Fig. 6 Change in per Capita CO_2 emissions and GDP, Brazil. Reference: https://ourworldindata.org/grapher/co2-emissions-and-gdp?time=2005..latest&country=~BRA

Table 1 Generation and reduction of carbon emissions in Brazil

S. No	Emission Type	Total Emissions (tCo_2)	Total Issuances of Certified Emission Reduction (tCo_2)	Carbon Credit Contribution (%)
1	Industrial	1287×10^6	134.21×10^6	10.43
2	Electricity & Heat Produce	774×10^6	158.75×10^6	20.51

6.1.2 China Carbon Emission and Reduction (2005–2018)

China is the top energy user emitter[11] globally and consumes 50% of the world's coal. China's President's recent commitment to going carbon neutral by 2060 (Bloomberg 2020) took the world by surprise. Being the giant consumer and emitter, their aggressive approach toward reducing carbon emission can reach its peak a bit early as per the schedule submitted under Paris Agreement (Brief 2019) (Fig. 7).

In China, the major acceleration in carbon emissions was due to increased coal consumption, primarily for electricity and heat production. Between 2005 and 2018, China has managed to compact its carbon intensity by 45.8% and enhanced the non-fossil fuels to 14.3% of its total primary energy mix (Layke 2019) (Table 3).

The total emission generated by significant China sources is compared with the project developed under the carbon credit mechanism with similar timelines. The

Table 2 Generation and reduction of carbon emissions in China

S. no	Emission type	Total emissions (tCo_2)	Total issuances of certified emission reduction (tCo_2)	Carbon credit contribution (%)
1	Industrial	$37{,}464 \times 10^6$	1216.91×10^6	3.25
2	Electricity and heat produce	$52{,}334 \times 10^6$	937.59×10^6	1.79

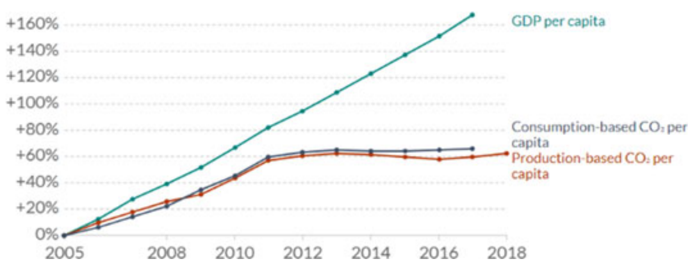

Fig. 7 Change in per Capita CO_2 emissions and GDP, China. Reference—https://ourworldindata.org/grapher/co2-emissions-and-gdp?time=2005..latest&country=~CHN l

[11] https://www.ucsusa.org/resources/each-countrys-share-co2-emissions.

carbon credits project demonstrates the contribution in the reduction of the national emissions by 3.25 and 1.79% in Industrial and Electricity and Heat Production sectors, respectively (IEA 2020, UNEP DTU 2020) (Fig. 8).

6.1.3 India Carbon Emission and Reduction (2005–2018)

The country is categorized under developing nations, but it has been ranked as the third largest emitter of GHG. Given that India has the world's second largest population with more than 1.3 billion (WBG 2019), these two figures go hand in hand. The country still has very low per capita emissions expected to grow as economic development happens (Ritchie and Roser 2017). The opportunity available for its population to implement low carbon development has global importance in combating climate change.

The total emissions generated by India's significant sources are compared with the project developed under the carbon credit mechanism with similar timelines. The carbon credits project demonstrates the contribution in reducing the national emissions by 4.63 and 1.73% in Industrial and Electricity & Heat Production sectors, respectively (IEA 2020, UNEP DTU 2020).

Table 3 Generation and reduction of carbon emissions in India

S. no	Emission type	Total Emissions (tCo_2)	Total issuances of certified emission reduction (tCo_2)	Carbon credit contribution (%)
1	Industrial	5853×10^6	270.79×10^6	4.63
2	Electricity and heat produce	$12{,}234 \times 10^6$	217.78×10^6	1.78

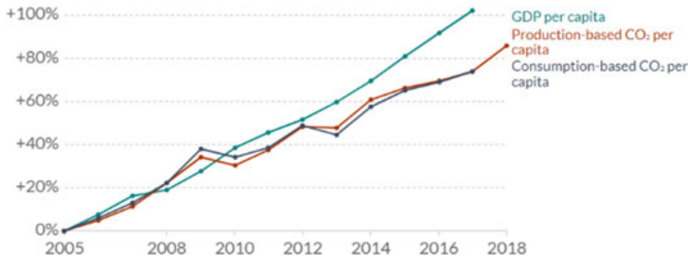

Fig. 8 Change in per Capita CO_2 emissions and GDP, India. Reference: https://ourworldindata.org/grapher/co2-emissions-and-gdp?time=2005..latest&country=~IND

7 Paris Agreement—Implementation Pillars

The Paris Agreement implementation plan focuses on three essential pillars, which focus on Capacity Building, Finance, and Technology Transfer. Countries' climate commitments so far are highly dependent on these pillars, especially for emerging economies, where there is a massive scope of emission reduction by linking low carbon development pathways.

7.1 Capacity Building

The responsibility of emission reduction is jointly shared by developed, developing, and least developing countries, however, there is a significant capacity gap between the countries to implement the NDCs. The Paris Agreement of Article 11 specifically highlights the importance of strengthening the capacities. Support is to be provided to developing and least developing countries toward adaptation and mitigation activities. Article 11, also highlights that nations with least power, namely "the least developed countries and those that are particularly vulnerable to the adverse effects of climate change, such as small island developing States," are termed, recipients.

7.2 Finance

Conditional and unconditional pledges describe the need for climate financing. Article 9 of the agreement quantifies the financial commitment needed by developed nations at $100 billion. Requirements do not explicitly match the sources of financial obligations. The guidelines of market-based approaches will be expected to address the existing financial gaps for climate action. The knowledge and resources of existing carbon markets will help establish new mechanisms that are expected to be more transparent and accountable under the universal system.

7.3 Technology Transfer

The target focus of net-zero emission through mitigation approaches underlines the increasing operational and technological efficiency of various emission facilities. In the Paris Agreement, Article 10 defines the long-term purpose of fully understanding technology development and transfer "to improve resilience to climate change and to reduce greenhouse gas emissions." In Article 4, it is guided that all the parties shall support and cooperate in the transfer of technology and development of a new system that reduces GHG emissions.

8 Analysis of Climate Commitments (NDCs)

There are commitments made by maximum countries as per the Paris agreement. However, the existing obligations are also critical to keep the global emissions within 1.5°, but there are still gaps that reflect that the current NDC is insufficient. A quick analysis of national commitments of a few countries is given below in various scenarios:

Based on the commitments made by different countries to hold global warming below 2 °C, climate tracker has cross-checked the national emissions and their future contribution to global emission. The various scenario envisaged are:

- Critically Insufficient: The countries coming under this category represent the commitments made so far are not in line with 2 °C. With this range, global warming will be greater than 4 °C if everybody follows the same approach.
- Highly Insufficient: The countries coming under this category represent the commitments made so far will fall in the range of 3–4 °C.
- Insufficient: This category of countries is close to keep the target of 2 °C; however, there is a need to increase the target slightly
- Compatible: All the countries in this range are following the 2009 Copenhagen 2 °C goal but still not consistent with Paris Agreement
- Paris Agreement Compatible: This category represents the ambition of Paris agreement to keep the global warming up to 1.5 °C, it is intended that all the countries should fall under this category in line with their national commitments
- Role Model: This is more than the required scenario in which countries are well ahead on the climate action plan of the Paris Agreement

The Table 4 represents that more than 70% of the existing commitments are falling under Critically Insufficient, Highly Insufficient, and Insufficient. There is a need to make an extra push in policy, governance, and finance to achieve the global emission reduction mission.

9 Carbon Credit: Finance Tool for Climate Action

The Intergovernmental Panel on Climate Change's 2018 special report on 1.5° hardly left any time and reinforced the urgency of climate action. The scenario of 1.5° 570 Gt in 2018 is diminishing, and the energy sector required $2.4 trillion in investments each year till 2030 to undergo the necessary transformation (Thwaites et al. 2020).

On analyzing the carbon pricing of five emission trading systems already in place and operational, the average price range in 2019 is 17.6 USD.[12] By reviving the international carbon market mechanism after the introduction of new terms, the climate finance requirement can partially be fulfilled (Fig. 9).

[12] https://icapcarbonaction.com/en/ets-prices

Table 4. NDC Commitments by countries in Paris Agreement

	4°C+ Critically Insufficient	<4°C+ Highly Insufficient	<3°C+ Insufficient	<2°C+ Compatible	<1.5°C+ Paris Agreement Compatible	<<1.5°C+ Role Model
Argentina	■					
Australia			■			
Bhutan				■		
Brazil			■			
Canada			■			
Chile			■			
China		■				
Costa Rica				■		
EU			■			
Ethiopia				■		
Germany						
India				■		
Indonesia		■				
Japan		■				
Kazakhstan			■			
Kenya				■		
Mexico			■			
Morocco					■	
New Zealand			■			
Norway			■			
Peru			■			
Philippines				■		
Russian Federation	■					
Saudi Arabia	■					
Singapore		■				
South Africa		■				
South Korea		■				
Switzerland			■			
The Gambia					■	
Turkey	■					
UAE		■				
USA	■					
Ukraine	■					
Vietnam	■					

Source https://climateactiontracker.org/

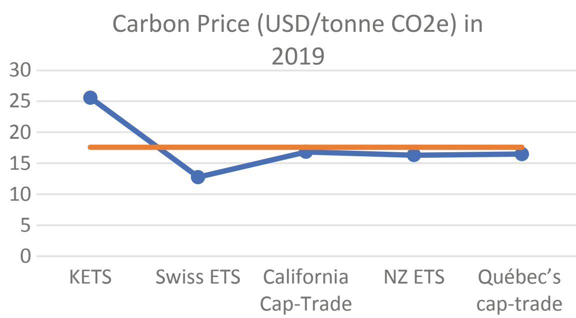

Fig. 9 Carbon price under emission trading scheme

Paris Agreement (United Nations 2015)

"Developed country Parties shall provide financial resources to assist developing country Parties concerning both mitigation and adaptation in continuation of their existing obligations under the Convention."—Article 9.1

The Financing of the Paris Agreement is explained in Article 9, which re-establishes the guidance that developed nations should take the steering role in mobilizing finance (Article 9.3). The details of finance pledged and provided will be biennially communicated by developed countries (Articles 9.5 and 9.7). The developing nations can also contribute to financing voluntarily (Article 9.2). The monetary transaction provision should contribute to maintaining a balance between Adaptation and mitigation (Article 9.4). Article 6 of the Paris Agreement use of market-based mechanisms, which may also extend a source of finance for mitigation and adaptation actions

The target set by the world to achieve the global emission reduction target comes with a clause of "Conditional" and "Unconditional." The conditional clause describes that the target will only be met if the required support will be available. The significant components of support expected by countries comprise of capacity building, financing, and technology transfer. However, under the unconditional clause, all the required support will be arranged by the country itself. The financing required to meet NDC becomes more critical as market-based approaches are yet to be clarified. Some explanations limit Article 6 mechanisms to the conditional clause of the NDCs, which should be considered the baseline for mitigation interventions. In contrast, some nations would instead allow crediting to contribute to the unconditional elements and targets of the NDCs (Schneider et al. 2017).

The consolidated scale on which the developing country required climate finance was $ 3,534 bn until October 2015, based on the information disclosed by nations to their NDCs. Of these, $81 billion and $407 billion were requested from the domestic and international markets, respectively, while further clarity on the type of financing is needed for the remaining amount. The global market sources include public funds, private investments, and carbon markets (Yeo 2015). They are considering the pipeline of voluntary carbon market projects, especially the Gold Standard, which has the potential of generating 170 million tonnes of CO_2 every year (Gold Standard 2020). The total potential of climate finance mobilization through Gold Standard projects within ten years will be $29.92 bn, assuming the average carbon price of five ETS in 2019.

10 Challenges with Carbon Credit

The awareness toward climate action and environmental concerns also highlight the possible solution like carbon credit. Though there are different opinions related to carbon credits, this market mechanism is still operational and expected to continue further under the Paris Agreement, with additional terms. Some of the current concerns which should be taken into account are:

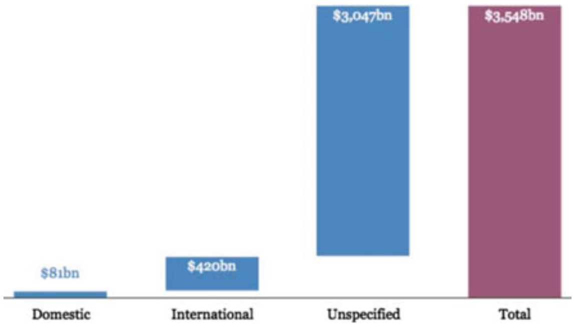

Fig. 10 Climate Finance Request in INDCs. Reference – Carbon Brief 2015

10.1 Real Emission Reduction

Unlike the allowances used in cap-and-trade markets, carbon credits always represent real emission reduction from the atmosphere somewhere in the world. However, the process of assessing the actual overall impact on global emission by carbon credit is not clear because they are designed to be part of the overall reduction strategy, not a replacement for other solutions.

10.2 Actual Monetary Value

The actual value of carbon credit should be more expensive to reflect the actual cost of climate change. There is a big difference in the price of emission reductions by various countries as the vulnerability index and baseline infrastructure also contribute to estimating carbon credits' actual monetary value. The current carbon markets are not mature to reflect the real cost of carbon abatement.

10.3 Additionality

The concerns on the fundamentals of carbon methodologies and how emission reductions are calculated are being challenged nowadays by different think tanks/governments. The need for climate finance to make the project financially viable requires critical review. The ongoing climate negotiations are still deliberating on the existing inventory of carbon credits which seems to be a business case as usual scenario for some projects. A good number of changes are already introduced at various level, and it is anticipated that the carbon market after 2020 will take stringent measures to fix this challenge.

10.4 Double Counting

This is related to the overall accounting system of carbon credits interlinked with compliance and voluntary carbon market. The challenge of double counting arises if two or more entities claim the same emission reduction toward their GHG targets: one entity could be the host country where the project is implemented and other entity responsible for financing. If the single units of carbon credits claimed are twice for their NDC, it impacts the market's integrity and makes the overall plan less ambitious in achieving the respective NDCs (Cames et al. 2016).

10.5 License to Pollute

There is a severe concern about the intentions of carbon credit buyers. The emission reduction by purchasing the carbon credits should only be considered the last option under the carbon reduction strategy. The carbon market provides an opportunity to offset such emissions which cannot be further reduced or avoided by other interventions like technology and operational efficiency. Though the concept of "Green-washing" is not valid for all, there is a need to utilize the carbon market to meet the global targets instead of considering an escape way from obligations.

11 Carbon Markets After 2020

There is a lot of confusion in the air regarding the rules and regulation of future carbon market. The past experiences make it very clear that regulatory uncertainty is quite common for carbon markets. There are many speculations on the future of carbon credits under the Paris Agreement and a big question mark on the transition of the existing carbon market project into Paris Agreement. On the contrary, many new programs and market developments have taken place in the last 5 years that support carbon credits' future in the long run. Some of the programs/schemes are discussed below in brief:

11.1 Korean Emission Trading Scheme (KETS)

East Asia's first mandatory Emission Trading System (ETS), The Korean Emission Trading Scheme (KETS) came into being on 1 January 2015. Presently, an ambitious demand to achieve 38 million international carbon credits is expected under KETS by 2030. Put differently; it would enable them to achieve Korea's NDC target of 37% below BAU (536 MtCO2e), which represents a 22% reduction below 2012 GHG levels (NDC). Covering more than 600 Korean largest emitters that are responsible for contributing 70% of national GHG emissions, the ETS is only behind the EU ETS in terms of the carbon market size.

11.2 Switzerland Emission Trading System (Swiss ETS)

Purely on voluntary beginnings, The Switzerland (Swiss) ETS[13] was initiated in 2008. Twelve years later, in January 2020 in a bid to expand its sector coverage to domestic aviation as well as to fossil-thermal power plants, the Swiss ETS linked itself with the EU ETS. This was to mainstream itself with NDC's emission reduction target of 50% by 2030 from 1990 GHG levels.

The international carbon credit from least developing countries registered and implemented after 2012 are allowed in the ETS. The current pricing of per ton CO_2e is 12.78 USD.

11.3 USA–California Cap-and-Trade Program

Realizing the threat of climate change and curb the continued increase in GHG emissions, the United States of America put The California program[14] in place. A legislative directive in 2017 insisted on a cap-and-trade system post-2020 to expedite the attainment of California's climate goals. The California program is expected to cover 80% of the State's GHG emissions. The programme aims to reduce GHG emissions by 40 percent by 2030 from 1990 GHG levels by targeting extensive industrial installations with over 25,000 tCO_2e/year emissions. The current pricing of per ton CO_2e is 16.84 USD.

11.4 New Zealand Emissions Trading Scheme (NZ ETS)

Integrated into International carbon market under the Kyoto Protocol, the NZ ETS underwent a process change in June 2015. The new development saw the NZ ETS transform into the domestic system. As an effective strategy to meet its NDC and 2030 target, linkages to international carbon markets could be a defining factor for New Zealand. The GHG emission reduction target is for 30% by 2030 from 2005 GHG levels. The current pricing of per ton CO_2e is 16.33 USD.

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13 https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=64.

14 https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program.

11.5 Canada–Québec's Cap-and-Trade System

Although Quebec was a member of the Western Climate Initiative from 2008 onward, its GHG emissions cap-and-trade system was introduced only in 2012. The 3-year-long compliance obligations were initiated a year later. In 2014, Quebec formally linked its system with California. Four years later, in January 2018, they also got linked with Ontario. The program aimed facilities with more than 25,000 tCO_2e/Year emissions. However, as of 2016, it also included fuel distributors that exceeded the limit of distributing 200L or more of fuel in the previous year. The inclusion is independent of whether the fuel emissions were less than 25,000 tCO_2e or not. The program looks at achieving GHG emission reduction target of 37.5% by 2030 from 1990 GHG levels. The current pricing of per ton CO_2e is 16.48 USD.

12 Carbon Credit in Aviation Sector

Under the Paris Agreement, most of the emission generation scope are already covered. However, under the transport sub-sectors, specifically air and maritime transport are being handled by separate process and agreements. The fuels used in these sectors are known as bunker fuel (Schnurr and Walker 2019), and GHG emissions from bunker fuel were on climate negotiation plan since 1995. The ICAO has addressed the policy regulations on emission reduction under the mandate of the Kyoto Protocol.

In 2016, the international aviation contributed 1.7% of global CO_2 emissions by burning the fuel for combustion. In absolute terms, 560 million tonnes of CO_2 by international aviation is equivalent to total GHG emissions of Australia (547 million tonnes of CO_2) in 2016 (UNFCCC 2019i).

Though a lot of effort has been made to reduce aviation and maritime emissions by technological and operational improvements, an annual average growth of 4% and 2.6% is witnessed in aviation and naval transport since 2012. In case the aviation and shipping sector's situation remains unaddressed, both aviation and shipping will contribute 20%–50% among the global CO2 emissions by 2050 (Cames et al. 2015).

In 2016, ICAO launched a new global scheme named CORSIA (Carbon Offset and Reduction Scheme for International Aviation). It aimed to achieve carbon-neutral growth between 2021 and 2035. This global scheme created a massive demand for carbon credit as 2021 flights have to offset their emission growth from average emission levels of 2019/2020. The deliberation will use existing carbon credits from the CDM project under the CORSIA scheme (Warnecke et al. 2019).

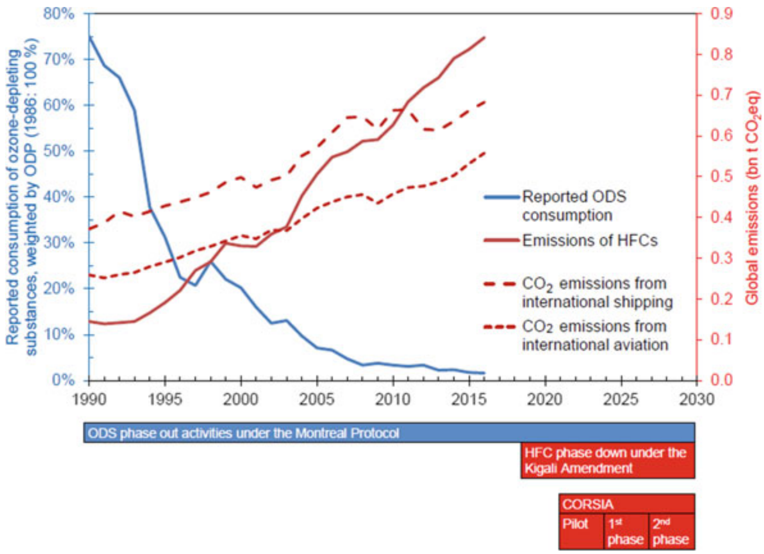

Fig. 11 Global emission by aviation and shipping sector and its impacts

13 Carbon Credit and Sustainable Development

The carbon credits are regulated by different governance structure in which the primary dominant system is the UNFCCC framework wherein the CDM projects are developed. In the past decade, especially under the voluntary carbon market, the emission reduction units have added more values to climate action. There is different governance structure under the voluntary carbon market those are also aligned with other sustainable development indicators like SDG 3, SDG5 and others. The analysis of various carbon standards and their scope to cover other value additions focusing on fragile and vulnerable communities is provided below:

Gold Standard Foundation is a decent carbon standard in the voluntary carbon market and is known for adding carbon credit from a sustainable development perspective. The impact of climate change is devastating for smallholder farmers worldwide as the impacting food system and threats to agriculture-based livelihoods. There are approximately 1.5 million Fairtrade producers in developing countries to design a climate-resilient program. Gold Standard and Fairtrade International jointly developed a Fairtrade Climate Standard, as a way to support smallholders and rural communities to produce Fairtrade Carbon Credits and gain access to the carbon market. The Fairtrade Climate Standard offers Fairtrade Carbon Credits an additional requirement over to Gold Standard certification. It makes a balance between emission saving and sustainable development (Figs. 11 and 12).

Under the Paris Agreement, there is new activity-based SDM for countries to achieve their NDC goals by utilizing carbon credits. To accelerate the process of mobilizing carbon finance to the developing countries for multiple SDG benefits, the

METHODOLOGY	CDM / CER'S	VCS	GOLD STANDARD	CCBA/PLAN VIVO	FAIRTRADE CLIMATE STANDARD
Reliability/ transparency	+	+	+	+	+
Participation stakeholders	+	+	+	+	+
Local communities own Carbon Credits	-	OPTIONAL	OPTIONAL	+	+
Benefit-sharing (e.g. premium for adaptation)	-	-	-	OPTIONAL	+
CO_2 reduction end user	-	-	-	-	+
Minimum price covers project costs	-	-	-	-	+

Fig. 12 Comparison of International Carbon Standard *Source* Fair Climate Fund https://fairclimatefund.nl/en/our-approach/fairtrade-climate-neutral

world bank has already designed and tested the standardized crediting framework (SCF)[15] to ensure the systematic approach toward economic and social services and emission reductions. The framework seems to be quite promising toward article 6 activities under the Paris Agreement.

14 Conclusion

There is a lot of regulatory uncertainty on the prospects of carbon credits due to the Kyoto Protocol's transition to a new climate regime under the Paris Agreement. There is a need to design and develop innovative market-based mechanisms to mobilize climate action required finance. So far, article 6 of the Paris agreement has been considered a bottleneck to finalize the rulebook and guidelines to operate a market-based mechanism. The carbon credit financial instrument is the only operational tool which is currently available. It is improbable to eliminate the carbon credit mechanism from a climate action plan to meet global targets.

Under the Paris Agreement, it is intended to mobilize private sector financing, and the approach of carbon markets can be instrumental in that. However, it will be a big mistake to consider carbon credit as an ultimate solution to achieve the Paris Agreement's long-term goal. There is a need to revisit the fundamentals of carbon credits like additionality, environmental integrity, and sustainable development before integrating into the global emission target. There is a need to increase the carbon price to reflect the real cost of GHG emissions abatement. Emerging economies like Brazil, China, and India wherein the future emissions will follow the uptrend due to economic development; a low carbon investment can be mobilized through carbon markets to build a climate-resilient economy.

The demand for voluntary carbon credits increased after 2012 as some private companies do it voluntarily as a part of their sustainability strategy to achieve climate justice. It is expected that the scope of reducing the emissions reduction under the Paris Agreement and keeping the ambition higher will increase the demand of international carbon credit in both compliance and voluntary carbon market. In the coming year, the relationship between carbon credit and climate change will further legitimate its impact. An integrated approach would bring the world closer to the long-term ambition of 1.5 °C.

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Community Resilience to Climate Change

Debbie Bartlett

Abstract This chapter provides a brief introduction to the ways in which communities and local authorities can take action to mitigate some of the most common effects of climate and environmental change experienced in the urban environment. While the Urban Heat Island phenomenon and the potential for green and blue infrastructure to reduce this is well known, less attention has been paid to impacts felt by people at street or neighbourhood scale. Increasing tree cover and vegetation is (almost) always to be applauded and has the added benefit of contributing to drawdown and carbon capture, particularly when trees are young and actively growing. Here, a range of options are described and an integrated approach to incorporating Nature-based Solutions in land use planning, combined with net-zero initiatives, is suggested as the most effective way forward for sustainable resilient communities.

Keywords Resilience · Nature-based solutions · Heat stress · Floods

1 Introduction

The focus of this chapter is the strategies to increase community resilience to climate change, specifically the impacts of global warming, increasing heat waves, and extreme rainfall events in the urban environment. While attempts are underway at global, national, regional, and local scales to reduce the rate of emissions, this will not prevent the situation from getting worse; only when drawdown and carbon sequestration exceed emissions will there be any move towards achieving stability.

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2 The World is Getting Hotter

How much hotter and how fast is uncertain. The effects of 1.5 °C rise in global temperature will be less extreme when compared to 2 °C (IPCC 2018). However, even living under this more optimistic scenario will be challenging and the effect on human activities and natural systems will be severe; adaptive capacity has limits. Even in temperate regions such as northern Europe, global warming is now a reality with regular heatwaves and I now live surrounded by vineyards with wine produced in my village. This would have been unimaginable 20 years ago.

2.1 The Urban Heat Island Effect

The Urban Heat Island (UHI) effect is the well-known phenomenon of built-up areas being warmer than the countryside after the sun has gone down. The cause of the UHI effect is complex but a key component is the density of buildings, which can reduce airflow and funnel wind through the 'canyons' made by narrow, high sided, streets. The geometry of the built environment also reduces 'sky view', the degree of openness to the atmosphere that allows heat to dissipate. A further factor is that many building materials absorb and store heat, releasing it when the air temperature drops as evening draws in, particularly after hot days. The result is high night time temperatures that make it difficult to sleep and can adversely affect the old, the young and otherwise vulnerable groups including pregnant women.

Loss of sleep can have both short-term consequences, for example, an inability to concentrate fully on activities the following day, with safety implications for those driving or operating machinery, and educational performance, as well as potential long-term health effects (Medic et al. 2017). Liu et al. (2020) analysed the correlation between Surface Urban Heat Island Intensity (SUHII) and Gross Domestic Product (GDP) for 259 cities in China between 2000 and 2015 and identified the need for a more climate-friendly approach to the urban environment for economic development. Costa et al. (2016) predicted that economic loss due to heat-induced decline in productivity could reach 0.4% of Gross Value Added (GVA); for London, UK, this could total €1.9 billion emphasising the potential severity of the financial cost.

While the Urban Heat Island effect is usually considered to be most significant at night, there are also significant effects experienced due to rising daytime temperatures, especially as the frequency of heatwaves is increasing and these are being experienced across the globe (Seneviratne et al. 2012).

2.2 Heat Stress

Campbell et al. (2018) conducted a systematic review of the research into health of heatwaves and found that most studies had been conducted in high income mid-latitude countries while the impact on countries, such as those in the global south, most at risk from extreme heat were under-represented. These authors also highlighted that death rather than morbidity was used as the indicator of impact. Even in the United Kingdom—a temperate zone country—it is predicted that heat-related deaths will increase by around 250% by the 2050s modelled using the lower estimated scenario for global warming (Kovats and Osborn 2016). Less extreme—but significant—consequences are likely to be experienced in the working population, particularly those working out of doors or in confined conditions such as factories. Lundgren et al. (2013) explored this and highlighted the potential for heat stress to affect productivity at global scale and to disproportionately affect developing countries in the tropical climate zone. There has been interest in economic impacts, particularly in Australia (Zander et al. 2015) for some time and there is evidence of emerging interest in this topic with recent papers on the impact on workers in Brazil and need to consider heat stress in working conditions and employment legislation (Bitencourt et al. 2020), in India (Rao et al. 2020) and Thailand (Boonruksa et al. 2020). While the economic consequences resulting from heat stress on these groups is apparent, there are less obvious consequences, for example, on general wellbeing, unwillingness to undertake exercise, and increased healthcare costs for vulnerable groups, as well as the recently revealed long-term, cumulative, effects on children's learning abilities, which is predicted to impact future macroeconomic growth (Park et al. 2020).

Infrastructure is also affected by heat. Bridges, including the well-known Tower Bridge in London, UK, became stuck open in 2019, road surfaces melted resulting in vehicles becoming stuck and railway tracks distorted causing delays, cancellations and potentially accidents. These phenomena are widely reported in the media and have cost implications, either for Government or the private sector making demands on budgets, passed on in taxation, charges, or fare increases to the public. There are clearly also implications of heat stress and likely associated drought on drinking water supplies, productivity of agricultural crops and livestock, as well as on wildlife and natural vegetation with implications for ecosystem service provision in the short term and into the future. The devastating effect of wildfires in California, United States of America (USA), and in Australia have received worldwide media attention and, at a smaller scale, have also been experienced in England and Mediterranean countries.

2.3 Community Adaptation—Learning from the Past

Historically, communities have evolved with their ambient conditions and developed many kinds of effective adaptive strategies these are evident, for example, in different architectural styles, with buildings in hot countries designed to maximise ventilation, often painted white to be reflective, and including shaded courtyards. Daily routines, such as resting in the middle of the day and working in early morning and evening, as well as type of clothing, colour, and material, are all examples of community adaptation. Those in temperate areas in the north can learn from those with experience of hot weather, for example, in the UK we could move to the Mediterranean habit of a long midday break extending the working day to compensate. However, those in the global south, the most likely to be most seriously affected (Lundgren et al. 2013) as heatwaves become more frequent and extreme, will need a different approach to meet future challenges.

3 Global Increase in Frequency and Intensity of Extreme Weather Events

In addition to increase in average temperatures and intense heatwaves, severe storms have become more frequent in recent years, typically of greater intensity than those previously experienced. These have been widely covered in the media but to give a few examples from 2019:

- Hurricane 'Dorian' was the second strongest ever recorded in the Atlantic affecting the Bahamas and moving on to Western Canada.
- Cyclone 'Idai' caused deaths in Mozambique, Zimbabwe, Malawi, and Madagascar.
- Typhoon 'Hagibis' caused extensive damage in Japan.

(Masters 2020)

These have caused damage to buildings and infrastructure disrupting services, causing displacement and significant economic and social consequences—as well as human misery—requiring lengthy recovery periods. The psychological impact on those experiencing repeat events can only be imagined.

3.1 Flooding

Kayaga et al. (2020) investigated the impact of flooding and heatwaves on water and electricity supply in low-income urban settlements in Ghana, Africa. They found increased demand for both commodities in response to heat, in water for drinking and irrigating home gardens, and electricity for refrigeration. Ghana depends on hydropower for about 40% of electricity generation, so drought exacerbates these issues by reducing river flow. Conversely during flood events, water frequently becomes contaminated and power supplies are cut off. Similar challenges will be faced by supply companies and low-income settlements across the globe and building resilience into the supply infrastructure is an increasing priority requiring investment.

In 2019, the USA experienced its wettest January and July 2018–June 2019 was the wettest 12 months ever recorded in the history of the continent (Masters 2020). While rain may be a source of celebration in some countries, particularly those with monsoon cycles, it can also be a disaster. For example, the Indian monsoon of 2019 arrived late, and the rain was about 10% more than average. While this replenished aquifers, addressing water shortage, and was welcomed by farmers, it also caused extensive flooding which was the direct cause of the death of almost 2,000 people (Masters 2020). In addition to death by drowning, heavy rainfall has, perhaps surprisingly, been found to be associated with increased occurrence of ischaemic stroke, leading to health warnings, particularly for males over 65 (Tang et al. 2020). Flooding increases risk of waterborne disease outbreaks, for example, typhoid and cholera as well as those spread by mosquitoes, including malaria and dengue fever (World Health Organisation, undated). Additional problems are experienced in coastal areas when storm surges increase the height of tides, and this is compounded by river discharge into the sea. Hendry et al. (2019) assessed the potential for this combination to cause flood events around the UK and suggest that current flood risk assessments do not adequately take the cumulative impact into account. High tides and surges, particularly after a period of drought, caused saltwater to infiltrate aquifers' increasing salinity.

4 The 'Wicked' Problem

The term 'wicked problem' was first proposed by Rittel and Webber (1973) and applied to the complexities involved in identifying solutions to planning and social policy problems. These authors outlined ten characteristics of these problems, including multiple possible solutions, that the problem is symptomatic of other problematic issues and that defining an end point, i.e., when the 'problem' has been solved, may be impossible. Climate change is a good example. The preceding sections have demonstrated the many different effects that climate change—and to be more specific—changing weather patterns and events, are having on communities. The impacts are particularly extreme for those on low incomes, living in poor quality housing, and in vulnerable groups such as the old, the young, and those with existing health conditions or disabilities. Clearly, there is no simple solution. While effort is being made by countries across the world to reduce the rate of global warming by restricting emissions of greenhouse gases while simultaneously promoting carbon sequestration and drawdown by, for example, planting trees, even under the most optimistic scenarios, things are not going to get better any time soon; environmental change is occurring at an unprecedented rate and slowing this will be challenging.

There may well be more surprises in the future—the COVID-19 pandemic has clearly demonstrated the unimaginable can become a reality. The need for adaptation to increase resilience to changing environmental conditions is urgent. But how can this be done and where does responsibility for action lie? These questions will be explored in the following sections.

5 Developing Resilience for the Future

In the second half of the last century, space flight had put a man on the moon, agricultural productivity increased dramatically with mechanisation, fertilisers and pesticides, and the prevailing view was that all problems could be solved with modern science and technology. Climate change-related issues seriously challenge this view. Attention is increasingly turning to use nature to simultaneously benefit biodiversity and human wellbeing with the concept of Nature Based Solutions (NbS) adopted at the 2016 World Congress of IUCN[1] and now widely accepted at global, regional, and national scales.

NbS are defined by the IUCN as *"Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"*.[2] However, the European Commission, in transposing NbS into policy, gives a subtly different emphasis, stating that "*Nature-based solutions harness the power and sophistication of nature to turn environmental, social and economic challenges into innovation opportunities"* (European Commission 2015).

The Global Standard for NbS was launched in July 2020 after extensive consultation with potential users and identifies the following societal challenges as likely to benefit from the application of NbS:

- Climate change mitigation and adaptation;
- Disaster risk reduction;
- Economic and social development;
- Human health;
- Food security;
- Water security;
- Environmental degradation and biodiversity loss.

(IUCN 2020)

It will be readily apparent that the impacts of climate change on communities resonate closely with this list. I have been actively involved in promoting the NbS

[1] International Union for Conservation of Nature.

[2] See https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions.

approach for some time (e.g., Bartlett 2020) and in the following sections will discuss how these can be used to increase urban community resilience particularly with respect to the impact of heat waves, storms and floods.

5.1 Addressing the Urban Heat Island Effect

The larger and more densely developed a city is, the greater the UHI will be, with heat stored in the built fabric being released as air temperature drops as the sun goes down in the evening. This is widely understood, and the properties of construction materials are now included in the design process but there are cost implications. Traditionally, buildings in many parts of the world are painted white which reflects heat-reducing UHI potential. This strategy is now becoming more widespread with 'cool' pavements with reflective coatings promoted as a simple low-cost solution (Middel et al. 2020), however, Taleghani and Berardi (2018) found these materials could negatively affect pedestrian thermal comfort, making them feel hotter, and also increase wall and internal building temperature (Nouri 2015). A further issue is that manufacture of cool pavements requires more energy and carbon in manufacture than conventional ones (Gilbert et al. (2017). This is a complex area of significant current research interest, exploring options such as incorporating reflective material into paving. Macintyre and Heaviside (2019) explored the potential for cool roof technology to mitigate UHI in the UK and predicted this could reduce heatwave mortality by 25%. They suggested most benefit would result from this being applied to large commercial and industrial buildings rather than individual houses.

There is no doubt that the most effective way to address the UHI is to increase the proportion of green and blue elements in the built environment. This is clearly demonstrated by the effect Richmond Park, the large area of green space to the west of London, outlined with blue dots in Fig. 1, has. The park is not only cooler than the surroundings, but this effect extends beyond the boundary into nearby areas. Yu et al. (2020) carried out a critical review of the impact of green and blue infrastructure and reached the conclusion that these were both more cost-effective and politically acceptable than using cooling materials.

'Greening the grey' is a strategic approach to build resilience to climate effects, starting from considering the potential contribution any new development would make to the UHI at the Environmental Impact Assessment stage in the planning process, taking action to reduce this using design options as far as possible, and then mitigating residual effects. The Greater London Authority (2008) published a technical report on green roofs and walls to encourage these to be included more in planning applications and this has had marked effect with, for example, the prestigious high-rise Canary Wharf development now having around 6,000 square meters of green roofs. There are many examples of such 'green city' strategies and of commercial sector partnerships that enable these to be achieved. While visiting Nagpur, India, in 2018, I was impressed with the sheer scale of the Maha Metro initiative to develop

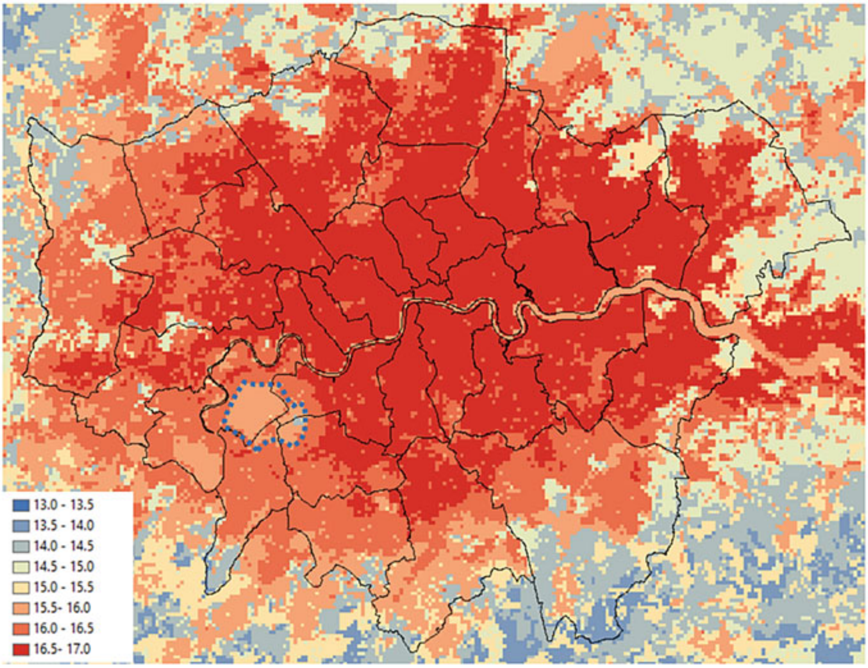

Fig. 1 Urban Heat Island Map for an average summer night. Note localised cooling effect of Richmond Park in the southwest of London. (*Source* Dataset available on the London Datastore. Project was carried out by VITO as part of an EU-funded RAMSES programme on the urban impacts of climate change)

vertical gardens on the 200 pillars raising the metro line above the road, part-funded by offering companies free advertising in exchange for sponsorship (Fig. 2).

While such strategies have real potential as additions to commercial developments, greater impact in residential areas is likely to come from tree planting. Urban forest initiatives are emerging, with the aim of increasing tree canopy cover at city scale and, although space is often at a premium, the multiple benefits—including wellbeing, biodiversity, air quality, and carbon capture—are a strong incentive. At the local level, communities are often active in protecting existing trees and small areas of green space, often referred to as pocket parks, and in their home gardens. Levé et al. (2019) have considered the cumulative effect of multiple small gardens within the urban fabric from the perspective of pollinators; this can be significant and encouraging individual and community gardening, a way for individuals to contribute to resilience.

Gober et al. (2010) investigated the potential for using water to mitigate UHI but water bodies need to be strategically placed as the most effect is felt downwind. Hathway and Sharples (2012) recorded an average reduction of 1 °C when air temperatures exceeded 20 °C and that this extended up to 30 m away from the river but was negligible at 40 m. They concluded streets opening onto the river, combined with riverbank vegetation, provided the most effective cooling.

Fig. 2 Vertical greenery on the pillars supporting the Nagpur Metro line (India, © Deepak Dhyani)

5.2 Thermal Comfort in Public Open Space

Bringing the focus from the city-wide to the local scale had resulted in increasing interest paid to street and neighbourhood strategies to reduce the impact of rising daytime temperatures and heatwaves. I am currently involved in the 'Cool Towns' Project,[3] funded by the European INTERREG 2 Seas programme and sub-titled '*Spatial Adaptation for Heat Resilience in Small and Medium Sized Cities*' (website: https://www.cooltowns.eu). This involves partners from Belgium, France, and the Netherlands as well as the UK, with the University of Greenwich, a member of the scientific advisory team. The focus is on public open spaces where people, particularly those who are vulnerable, might experience stress during hot weather, and on the small-scale interventions that can mitigate this by providing a retreat from the heat. Part of the rationale is that there are economic costs, particularly to urban businesses such as cafes, and shops with people are less likely to visit and spend money when the outdoor temperature is uncomfortable.

One of the outputs from this project will be a decision support toolkit to enable the costs and benefits of different Green Blue Infrastructure (GBI) interventions to be considered in a site-specific context enabling the most appropriate for the situation to be selected. There is surprisingly little real evidence on the impact green infrastructure has on cooling local microclimates, and even less on blue. Thermal comfort is not a function of air temperature alone but a combination of solar radiation, humidity,

[3] See https://www.interreg2seas.eu/nl/cooltowns.

and wind speed and direction as well as the level of activity and clothing worn. It is expressed as Physiological Equivalent Temperature or PET (Höppe 1999). The most effective way to reduce PET when feeling hot is to move into the shade—an option often taken by animals. Buildings provide shade as the sun moves across the sky and tree planting can add shade in areas where it is needed, such as in open squares and school playgrounds. Lee et al. (2020) found reduction in PET increased as trees were closer together in east–west facing street canyons, and Massetti et al. (2019) measured PET in the shade of similar trees planted in grass, asphalt, and gravel; those in grass were most effective in terms of pedestrian thermal comfort. Figure 3 shows Plane trees (*Platanus* × *acerifolia*), naturally large with a dense rounded head, trained on metal frames to maximise shade.

Where tree planting is not practical, for example in narrow streets, artificial shade in the form of awnings or canopies can be useful. Garcia-Nevado et al. (2020) reviewed the effect of shading devices and the use of different materials and recorded a reduction of up to 16^{0}C on street surface temperature. Colter et al. (2019) compared natural and artificial shade and concluded trees were most effective. However, there is increasing interest in artificial structures as protection against skin cancers, particularly in areas used by children, e.g., Holman et al. (2018). Two different approaches are illustrated in Fig. 4a and b.

Green walls and facades are having a surge in popularity, despite the capital and maintenance costs. Many claims are made about the benefits in terms of reducing

Fig. 3 Pruned trees (photo taken in Middleburg, the Netherlands, by the author)

a


Fig. 4 **a** Shade sails in a narrow street (Spain ©*Visa*). **b** Shade structure (Saudi Arabia ©*Sioen Industries*)

Fig. 5 A green wall on an office building (©*Sioen Industries*)

pollution, improving air quality and reducing noise but, although the insulating effects on internal building temperature are well established and they certainly improve the appearance of buildings, there is little evidence that they reduce outdoor temperatures significantly (Fig. 5). Water features, such as fountains, may have a greater psychological than physiological effect as any evaporative cooling may be cancelled by an increase in humidity that reduces thermal comfort. Despite this, water features, including fountains, remain popular features and landmarks (Fig. 6).

5.3 Surface Water Management

Flooding is a complex topic. Causation is not simply a function of the amount of water falling as rain but also the ability of the land to absorb it. In many cities, the original waterways have been canalised, culverted, or diverted through pipes, and buildings and roadways present impermeable surfaces—so where can the water go? If waterways are at capacity and/or drains are blocked, then it will result in surface water flooding or flash floods. The more developed an area, the more likely this is to become a problem for local communities.

Residents affected by flooding in the UK are swift to blame the authorities responsible for managing rivers demanding more dredging and silt removal in the belief that

Fig. 6 Water wall (photo taken outside Sheffield Railway Station, UK, taken by the author)

faster flow will take the water away. However, this is then likely to cause communities downstream the same problem as well as damaging the habitat and freshwater biodiversity. Yang et al. (2019) involved people in a citizen science project looking at the relationship between land use and flooding following Hurricane Harvey in the USA revealing a strong correlation with industrial areas inside the city and agricultural land uses in the surrounding area raising awareness of land use as a contributing factor. A successful approach initiated by a private water company in South West England, called 'UpStream Thinking,'[4] has now been widely adopted across the UK. This moves the focus of flood prevention from the places affected to assessing and improving water storage capacity across the entire river catchment. This is done by encouraging modification in agricultural practices, such as increasing tree planting on riverbanks, ploughing against the slope, and leaving vegetated buffer strips which can all reduce soil erosion and so sediment load. In some places, farmers are being financially compensated for managing riverside fields so these can be flooded when necessary and so reduce water flowing downstream, holding it back to protect densely populated urban areas (Cook et al. 2017). It is anticipated that direct payment for providing NbS in this way will increase in future.

Within urban areas, there are a variety of methods that can increase resilience to flooding at the neighbourhood scale and the general term for these is Sustainable

[4] A search on YouTube will find several videos detailing this approach.

Urban Drainage Systems, commonly shortened to SuDs. Davis and Naumann (2017) discuss in depth the potential for using these as Nature-based Solutions for urban flood resilience and there is a wide palette of options. While some, such as creating wetlands and retention ponds, require space, others are relatively simple; multiple small-scale interventions can cumulatively have a significant effect. Introducing porous paving, for example, using cellular blocks instead of solid paving or asphalt enables water to soak through to the soil beneath and, if vegetated, will have an additional cooling effect on surface temperature, as demonstrated in Fig. 7.

Tree pits are increasingly being used to provide ideal growing conditions while at the same time slowing the rate of flow of water into drains. Although requiring excavation of a relatively large volume of material for installation compared to the final visible footprint (see Fig. 8) and although the tree at the time of planting may be small, they are highly effective in mitigating runoff and removing pollution. The number required for the greatest effectiveness is proportional to that of hard surfaces (Grey et al. 2018).

Less technically demanding are simple rain gardens, where levels and slopes are used to direct surface water into planted areas which then act as soakaways. An even smaller scale approach is rainwater harvesting and storage, which be done by individuals and households using a variety of containers and devices, such as

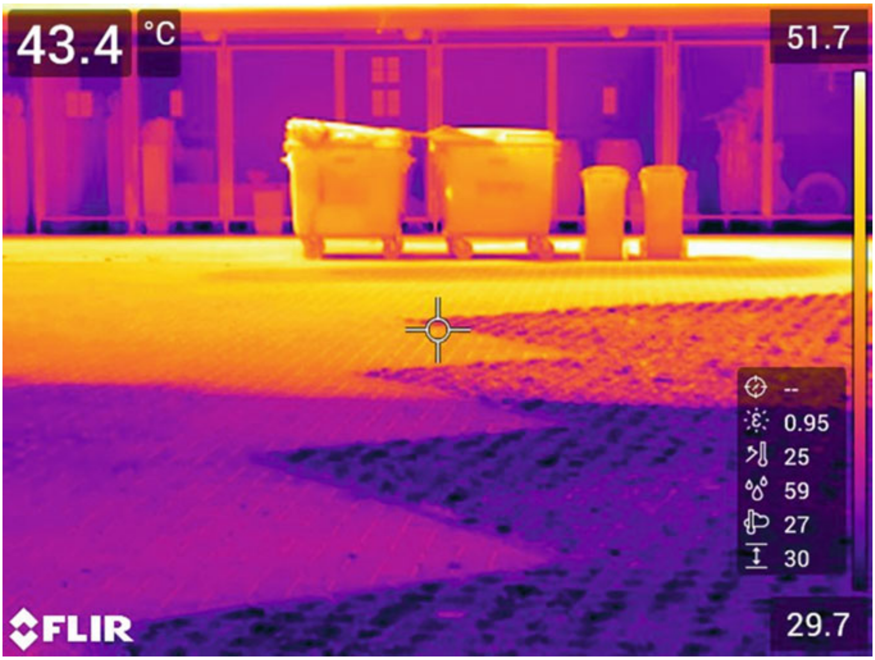

Fig. 7 Showing the temperature difference between vegetated and solid block paving in both full sun and shade (photo taken with a thermal imaging camera © Leen Meheuse)

Fig. 8 Trees planted in tree pits to prevent road runoff (North Street, Keighley, Yorkshire, UK. © GreenBlue Urban)

guttering collecting water from sloping roofs and channelling it down into water butts.

6 Integrated Land Use Planning for Community Resilience

The previous sections have outlined some of the key effects of global warming and extreme weather events, both symptoms of climate change, and ways these can be mitigated to increase community resilience. Some require intervention by the local or regional government while others can be driven from the local, neighbourhood level but, to be truly effective, an integrated urban design and management strategy with local action plans is most likely to be effective. An example of how this can be achieved is the 'Sponge City Program' adopted by the Chinese Government in 2013 to address the flooding associated with the rapid rate of development. The underlying concept is to hold water in the urban area by using Nature-based Solutions. This was piloted in 30 cities around the country and involved, for example, creating wetlands and planting trees (Qi et al. 2020). This has been highly successful and has now been extended both within China and beyond. While the main driver was flood resilience at the city scale, the interventions have also been effective in mitigating the Urban Heat Island effect and this synergy has increased the opportunity to develop public–private partnerships to attract funding (He et al. 2019).

The benefits of green and blue infrastructure are not limited to mitigation of heat stress and flooding but include multiple ecosystem services, for human health and wellbeing as well as wildlife. The 'green city' concept is gaining ground globally with the political and environmental agendas resonating in a way that leads to optimism for the future. However, I would like to leave you with a second wicked problem—Inequality. The communities most at risk from the effects of global warming and extreme weather are those with the least resources to enable them to increase their resilience; this is something we should all be working to address.

I would like to finish by asking how we can tell when resilience can be said to have been achieved. Although politicians and funders tend to focus on the completion of projects, developing community resilience is best considered as an ongoing process as we are living in times of rapid and unpredictable change. An adaptive management approach incorporating monitoring and evaluation of each initiative or intervention, however small, will enable learning from experience and applying this to adapt and develop resilience to future challenges.

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Realigning Developmental Programmes for Reducing Climate Vulnerability for Adaptation: *Case Study of Mahatma Gandhi National Rural Employment Guarantee Scheme in India*

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Abstract India is vulnerable, in varying degrees, to multiple disasters. The risks are compounded due to inherent vulnerabilities related to socio-economic conditions, environmental and climate change. India has several flagship programmes with large budgets, delivering serendipitous adaptation. The MGNREGS is one such programme implementing works related to Natural Resource Management. This chapter through analysis of the demand for works under the programme in relation to the average annual rainfall in the different states of India examines if there are any linkages between demand for jobs and annual rainfall. However, in contrast to the hypothesis, there is no clear relationship, and a mixed trend is seen with respect to work demand, employment provided, and mean annual rainfall. It clearly highlights that there exists a fundamental disconnect between the currently implemented development programmes and climate information in the different states of India, underpinning the need for a framework for mainstreaming climate information. The study suggests a generic strategy for mainstreaming adaptation in developmental programmes and argues that a transition from being 'reactive' to 'proactive' in approach will help build the resilience of systems and communities in the long-term.

Keywords Development · Mainstream · Climate risk · Vulnerability · Adaptation · MGNREGS

1 Introduction

Climate change is impacting natural resources and is projected to exacerbate, making vulnerability reduction and adaptation in all systems and communities a necessity. The increase in the land and ocean temperature since 1981 has been 0.18 °C per decade (NOAA 2019). This warming has not been uniform across the world, but the global averaged temperature shows that more areas are warming than cooling. Globally, the past five years have been the hottest on record, and extreme weather

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events have increased five-fold and economic losses increased by a factor of seven over the past 50 years.

Warming of surface temperature has caused the glaciers, polar ice sheets and freshwater ice to melt, contributing to unprecedented rise in sea level. Oceans have warmed and expanded with nearly a third of carbon dioxide emissions absorbed by the oceans. On the land surface, heatwaves have become more frequent, and storms and extreme weather events, such as hurricanes are being reported more and more frequently. Thus, climate change impacts are many and extend well beyond increases in temperature.

An assessment of climate change over the Indian region by The Ministry of Earth Sciences, Government of India reports changes in both temperature and rainfall during the historical period. A rise in temperature by 0.7 °C during 1901 to 2018 is reported. It also highlights that during the recent 30-year period of 1986 to 2015, India has recorded multiple extreme weather events including a rise in severe cyclonic storms over the Arabian Sea, heat waves, floods and droughts. In 2018 alone, extreme climate change events in India resulted in an economic loss of USD 37 billion, equivalent to 10% of the Indian budget in FY2019 (Eckstein et al. 2019).

Projections into future for temperature and rainfall for the end of the century (2099) show an increase by 4 °C or more, compared to the recent past (1976–2005), with more frequent heat waves persisting over longer durations. Mean annual and rainfall during the monsoon season is projected to increase but at the same time the variability is also projected to increase—with more frequent and intense heavy rainfall events, and extended dry spells. Sea level is projected to rise by 20—30 cm by the end century (Raghavan et al. 2020). This is a grave threat to 70% of livelihoods in India that are dependent on climate-sensitive sectors—agriculture, fisheries, and forests.

2 Impacts of Climate Change and Its Implications

The sensitivity of human systems to climate change-related impacts is experienced as changes in productivity of agro-ecological systems; economic losses due to extreme climate events; and changes in drivers of mortality—dependent on climate, including proliferation of infectious disease vectors in new regions (IPCC 2014a).

In India, the Second National Communications and the Biennial Update Report 2 submitted to the United Nations Framework Convention on Climate Change (UNFCCC) have highlighted the impacts of climate change on various sectors.

- **Water resources**: Changes in climate variables including temperature, rainfall and humidity are reported to have significant long term implications on the quality and quantity of water. In many river basins of India, precipitation is projected to increase up to 30% during 2040–2069 and up to 50% during 2070–2099, compared to observed data for the period 1971–2005 (Mishra and Lilhare 2016).

- **Forest ecosystems:** Forests in India are subjected to over extraction, livestock grazing, fires and other anthropogenic pressures. Climate change is an additional stress, making the forests more vulnerable.
- **Agriculture and allied sectors:** Climate determines agricultural productivity as factors like temperature and precipitation act either synergistically or antagonistically with other factors, affecting yield. Climate change is projected to reduce annual agricultural income in the range of 15—18% on an average, and up to 20—25% in unirrigated areas by end century (Pathak et al. 2012).
- **Human health:** Climate change has various impacts on human health, including rise in illness and deaths due to more frequent and intense heat waves, floods and droughts. High temperature could increase the level of 'climate altering pollutants' other than carbon dioxide, which could exacerbate cardio-respiratory and allergic diseases, and certain cancers (NAPCCHH 2018). Climate change may also lead to an increase in the transmission and spread of infectious diseases.

2.1 Climate Risks and Disasters

The impacts of climate change are evident in the numbers of disasters being reported globally. Globally, it has been reported that due to extreme weather events, economic losses over the last 20 years have risen by 151% compared to the period 1978–1998, resulting in a loss of US$ 2,245 billion (Pascaline and Rowena (2018). Pielke (2019) reports a 74% increase in weather-related-catastrophe losses since 1990. Globally, less than half of the reported losses are insured. However, in developing countries, the proportion of insured losses is well below 10%. This is despite the increasing number of loss events being recorded as a result of earthquakes, storms, floods and droughts over the years.

India is vulnerable, in varying degrees, to multiple disasters. The risks are compounded due to inherent vulnerabilities related to socio-economic conditions, environmental degradation, climate change, etc. In terms of fatalities due to extreme weather events in the year 2018, the Global Climate Risk Index 2020, ranks India first. Trend analysis using decadal data from EM-DAT database shows that their number have been continuously increasing. During 1998–2017, the average annual extreme weather events stood at 16 events compared to 10 events during 1978–97. This increase is reflected in the increasing trend of economic losses due to extreme weather events.

India's economic losses doubled in the last decade with cumulative losses for 2008–2017 estimated to be USD 45 billion compared to USD 20 billion during 1988–1997. Further, the severity of these events has been rising with passing years, as evident from the increasing damage. All these indicate trends in impact of climate change and the persisting biophysical and socio-economic vulnerability of systems which is likely to exacerbate in the future under committed warming and climate change.

Some sectors and regions have high stakes in terms of vulnerability, with respect to climate change. Also, there are likely differences in distributional consequences of measures taken to deal with such changes (Schneider and Sarukhan 2001). The challenges are thus multifold given large populations lack access to energy, water, nourishment and other basic needs, and climate change will exacerbate this challenge. Under these circumstances, development that mainstreams adaptation, considering current vulnerability and existing adaptive capacity is imperative.

3 Why Assess Climate Vulnerability?

Agriculture and rural communities are exposed to two kinds of climate related stresses—current climate variability and long-term climate change. Climate variability encompasses, inter-annual variability in the onset of monsoon, seasonal rainfall distribution, mid-cropping season rainfall deficit, drought and unseasonal rainfall events such as delayed arrival of sowing rains, high intensity rainfall during cropping season, harvest season rainfall and deficit rainfall. According to observational data in India, there is an increasing monsoon season rainfall variability, leading to fluctuating crop production, low crop productivity and water shortage for agriculture, livestock and domestic use and complete crop failure during certain years—adversely impacting the livelihoods of rural communities. The current climate variability, the on-going and the projected climate change could adversely impact food production, water availability, forest biodiversity, health, etc., making systems and populations vulnerable.

Climate vulnerability is defined as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change including climate variability and extremes" (IPCC 2007). The adverse impacts of climate change will be exacerbated in the coming decades, due to land degradation, ground water decline, poor agriculture and water management practices, and above all inherent vulnerabilities in systems and communities. Managing risks due to current climate variability can build resilience of natural ecosystems and socio-economic systems to help cope with current changes in climate as well as future changes, thereby limiting losses.

Adaptation to current climate risks and variability is the first step to long term adaptation (IPCC 2014b). The Government of India in its Nationally Determined Contributions (NDC) has also highlighted the need for "Adaptation to climate change by enhancing investments in development programmes in sectors vulnerable to climate change, particularly agriculture, water resources, the Himalayan region, coastal regions, health and disaster management". Delayed action to anticipated risks is sure to limit adaptation options and escalate costs. Thus, in order to ensure adaptation of natural ecosystems and socio-economic systems to future climate, vulnerability assessment is a must.

India has several large flagship programmes such as Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), National Rural Livelihood Mission (NRLM), Pradhan Mantri Krishi Sinchai Yojana (PMKSY), etc., with large budgets.

Many of these programmes deliver serendipitous adaptation—developmental activities undertaken incidentally result in adaptation benefits. There are a few programmes which are climate proofed to ensure their success even under a future changing climate. However considering climate change impacts and exacerbation of extreme events, there is a need to move from serendipitous adaptation to climate proofing to integrated adaptation—wherein activities undertaken to achieve development objectives deliver adaptation benefits. This is considered to be a more effective approach than discrete adaptation (Helena et al. 2014).

This concept is explored through an analysis of one of the largest social protection programmes in the world–the MGNREGA, and a generic strategy to mainstream adaptation in developmental programmes presented.

4 Mahatma Gandhi National Rural Employment Guarantee Act

The Mahatma Gandhi National Rural Employment Guarantee Act was passed by the Parliament of India in 2015. The programme is funded by the Government of India and during the financial year 2020–21, about ₹760 billion has been allocated. This programme promotes convergence with several developmental programmes.

In 2019–20, MGNREGA had a total 9.254 million works (including new + spill over). This programme or scheme was ranked as the world's largest public works programme (World Bank 2015), providing social security and leading to rural development across India. "MGNREGA aims at enhancing the livelihood security of people in rural areas by guaranteeing 100 days of wage-employment in a financial year to a rural household whose adult members volunteer to do unskilled manual work". The thrust of MGNREG Scheme (MGNREGS) is on "planning for works related to Natural Resource Management (NRM), agriculture and allied activities on public lands, and livelihood related works on individual land, leading to sustainable livelihoods and provisioning of livestock shelters for individual households" (MoRD 2019). Despite the scale, reach and NRM focus of the programme, very limited efforts have been made to explore the feasibility of using MGNREGS as a vehicle to deliver vulnerability reduction and adaptation to climate change. The only effort so far is by the DFID supported programme called Infrastructure for Climate Resilient Growth (http://ipetechnologies.com/icrg/).

4.1 Rationale for Considering MGNREGS for Vulnerability Reduction

There are four categories of MGNREGS works, largely related to natural resources such as cropland, grazing land, forests and water resources (Table 1).

Table 1 Examples of works or activities under MGNREGS with NRM focus

Category	Description
Category—A (public works relating to natural resources management)	– Water conservation and water harvesting structures, watershed management, micro and minor irrigation works, renovation of traditional water bodies; and – Afforestation, tree plantation, horticulture and land development work in common lands
Category—B (individual assets for vulnerable sections)	– Improving productivity of lands, by providing suitable infrastructure for irrigation; – Improving livelihoods through horticulture, sericulture, plantation, and farm forestry; – Creating infrastructure for promotion of livestock; – Development of fallow or waste lands; and – Unskilled wage component in construction of houses and creating infrastructure for promotion of fisheries
Category—C (common infrastructure for NRLM: compliant Self-Help Groups)	– Works for promoting agricultural productivity, common work-sheds for livelihood activities of Self-Help Group
Category—D (rural infrastructure)	– Works for all-weather rural road connectivity, rural sanitation, play fields, disaster preparedness or restoration of roads; – Construction of buildings for village counsels, women self-help groups' federations, cyclone shelters, food grain storage structures, building material required for construction works; and – Maintenance of rural public assets

Source Para 4(1), amended Schedule I of MGNREGA, 2005 (Babu et al. 2014)

The MGNREGS guidelines states: "the district programme coordinator should ensure that at least 60% of works taken up at the district level in terms of cost shall be for creation of productive assets, directly linked to agriculture and allied activities through development of land, water and trees" (Guidelines and Framework for 2020–21, dated 18th Sept. 2019). During 2019–20, 66% of the budget allocation was towards NRM works (http://mnregaweb4.nic.in/netnrega/all_lvl_details_dashboard_new.aspx).

MGNREGS-NRM works related to water and land development contribute to "generation of environmental benefits and natural resource conservation; ground water recharge, increased water availability for irrigation, increased soil fertility, reduced soil erosion, and improved tree cover" (Esteves et al. 2013). A study across four states (Esteves et al. 2013) has shown that many MGNREGS works such as application of silt to croplands and provision of irrigation can result in build-up of soil organic carbon (SOC), and carbon sequestration in biomass and soil when tree plantations and fruit orchards are raised, contributing to climate mitigation. In the 40 study villages, higher SOC content was recorded in 72% of the beneficiary plots sampled, compared to control plots. Likewise, in 31 of the 40 villages, carbon sequestration benefits—both in biomass and soil accrued when afforestation works were undertaken. These fruit trees and afforested areas when grown to maturity also provide economic benefits in the form of fruits, seeds and leaves, even in a drought year, supplementing the household income.

The above benefits of MGNREGS works have contributed positively to vulnerability reduction in agriculture and livelihoods. A study by Godfrey-Wood and Flower (2018) concluded that "MGNREGS has already made a major contribution to resilience to climate change, but requires improvements in governance and state capacity to maximize its contribution". Another study by the Institute of Economic Growth (Panda et al. 2018) concluded that the NRM component has brought substantial changes in MGNREGS operations and the assets created have increased irrigation water availability, ground water level, and agricultural productivity. Additionally, studies (Porras and Kaur 2018; Esteves et al. 2013; Tiwari et al. 2011; Sinha et al. n.d.) report that employment provided under MGNREGA and the type of works implemented, positively contribute to reducing vulnerability and building biophysical, social and economic resilience of rural communities. Thus, "MGNREGS meets the basic requirements to mainstreaming adaptation and it can become a multi-pronged strategy to reduce vulnerability to climate change in India" (Adam 2014).

The IPCC (2014c) defines resilience as "the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation".

Table 2 provides three indicators (Lisa et al. 2015) used to measure resilience (adaptation) and assesses how MGNREGS works or activities contribute to reducing vulnerability or building resilience or adaptation—based on impacts reported by published literature.

To summarise, some of the features of MGNREGS that make mainstreaming adaptation relevant and pertinent include: (i) large investment that has widespread reach; (ii) participatory programme that involves local communities in selection and approval of works to be implemented—a fundamental principle of adaptation; (iii) thrust on NRM related works, and (iv) vulnerability reduction potential.

Above all, there is a requirement under the new guidelines of MGNREGA to incorporate resilience—"Planning and design of works under MGNREGS should take into account, impacts of climate change in order to ensure resilience of vulnerable rural communities and make the benefits sustainable in the long run" (MoRD 2019).

In the following section, we analyse the demand for works under MGNREGS in relation to the average annual rainfall in the different states of India to elucidate if there exists any established linkages of MGNREGS providing jobs that help reduce vulnerability arising from failed agriculture crops or damage to crops in the event of a failed, or erratically distributed rainfall, or occasionally losses arising from crop loss to flooding events.

Table 2 Illustration of the contribution of MGNREGS works to vulnerability reduction and adaptation to climate change

Adaptation or resilience indicators	Activities under MGNREGS	Reported impact
Natural Resource Conservation (Tiwari et al. 2011; Esteves et al. 2013; Narayanan et al. 2014; Sinha et al. n.d.)	All NRM works including water conservation and harvesting works, land development works, afforestation, etc	• Increased area under irrigation, lowering risks of crop failure due to droughts • Increased net area cultivated, crop diversification and increased cropping intensities, leading to higher household agriculture incomes • Increased soil organic carbon and reduced soil erosion, leading to increased soil fertility, crop productivity and carbon sequestration • Biodiversity conservation and increased biomass stock leading carbon sequestration and provisioning of NTFPs that can provide alternate source of food and incomes • Increased water holding capacity of surface water bodies and improved ground water recharge has extended the number of days of irrigation and domestic water availability, reducing vulnerability
Disaster Risk Reduction and Management (Institute of Rural Management, 2010; Tiwari et al. 2011; Esteves et al. 2013; Narayanan et al. 2014; Sinha et al. n.d.)	Drought proofing works such as, afforestation/agroforestry; renovation and rejuvenation of traditional water bodies and springs; landslide and flood protection work; provisioning of extra 50 days of wage employment in drought affected areas	• Increased area under irrigation, lowering risks of crop failure due to droughts • Increased number of days of water availability from surface and ground water sources for irrigation, domestic use and livestock use • Growing of hardier fruit tree species that are more resilient than field crops to delayed rainfall or droughts • Increased biomass stock leading to carbon sequestration and provisioning of NTFPs that can provide alternate source of food and incomes • Additional 50 days of wage employment provisioned during drought prevents distress migration • Protection of lands from soil erosion and reduced surface runoff of flood waters

(continued)

Table 2 (continued)

Adaptation or resilience indicators	Activities under MGNREGS	Reported impact
Socio-economic/Livelihood Security (MoRD 2012; UNDP 2015; Vijay Korra, 2015; IGSSS, n.d.; Bhatia et al. 2016)	Bottom-up planning and selection of works for implementation; annual increase in wage rates; social inclusion (women, Below Poverty Line households, small and marginal farmers, SC and ST prioritization for provisioning of individual assets); endorsing the opening of bank accounts; convergence with other line departments; connectivity and other community development works	• Community participation in decision making—selection of MGNREGS works is a bottom-up process, where households participate in a Gram Sabha and propose a list of works following MGNREGA guidelines • Employment and income security—an increase in daily wage rates and income impacting on the household food and nutritional security; household health and overall wellbeing; reduced poverty, etc. • Improved access to information by local communities and convergence with other line departments provides access to information regarding other schemes Targeted betterment of poor and marginalised groups—empowerment of women through participation in planning and implementation of works and earning income; increased social inclusion with high participation of marginalized groups including SCs and STs

4.2 Annual Rainfall and MGNREGS Works—Demand and Employment

Rainfall distribution predominantly determines the cropping pattern and cropping intensity for a region. The expectation is for states with lower mean annual rainfall to have higher demand for MGNREGS works. This is based on the assumption that in regions with low rainfall, employment in agriculture and allied activities would be restricted to the kharif or monsoon season (i.e., months of June, July, August and September).

The trends in demand for works under MGNREGS in the different states are mixed (Fig. 1), contrary to expectation. Similarly, in contrast to the hypothesis that in low rainfall regions, a higher number of households would have been provided employment under MGNREGS, given the constraints to employment in agriculture and allied activities, a mixed trend is seen (Fig. 2) with respect to work demand and employment provided, and mean annual rainfall.

Another variable could provide insights into employment under MGNREGS and its relationship with rainfall, is the average person-days of employment generated

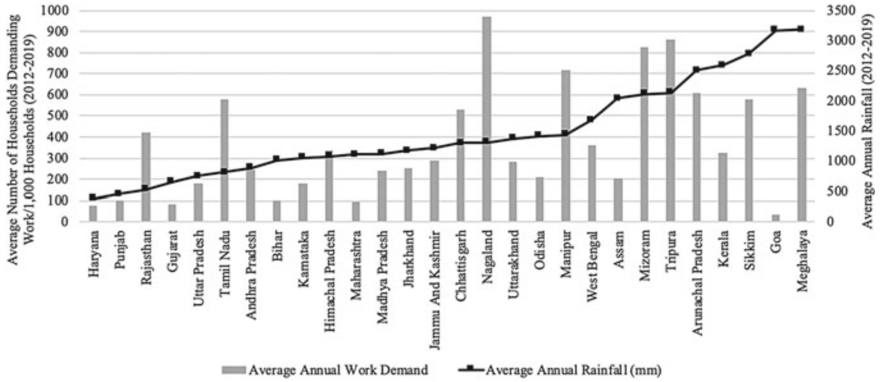

Fig. 1 Average number of households that demanded work standardized per 1,000 households against average annual rainfall during 2012–2019

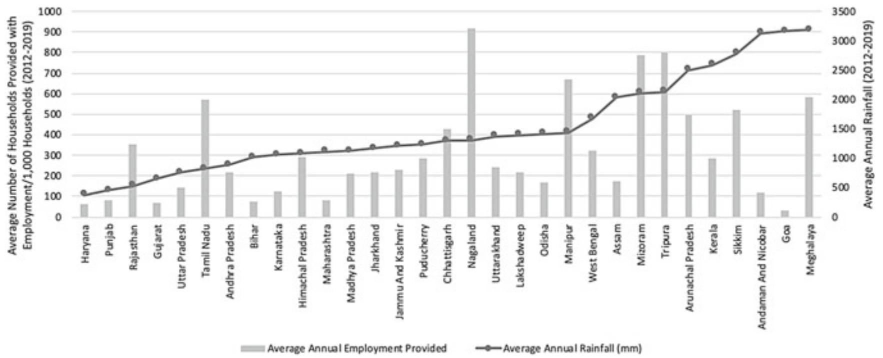

Fig. 2 Average number of households provided employment under MGNREGS standardized per 1,000 households against average annual rainfall during 2012–2019

per household. It can be seen from Fig. 3 that excluding the Northeast states, the average days of employment generated per household is generally high in the low rainfall states. Punjab and Haryana are exceptions where despite low rainfall, the average employment per household is low.

The analysis of the relationship between annual rainfall, which is the most critical factor that may contribute to demand for MGNREGS works and employment shows the following:

- There is no clear trend linking average annual rainfall with demand for MGNREGS works and employment generated.
  - In states with very high rainfall such as Kerala and Goa, very low demand for MGNREGS works and employment is recorded.

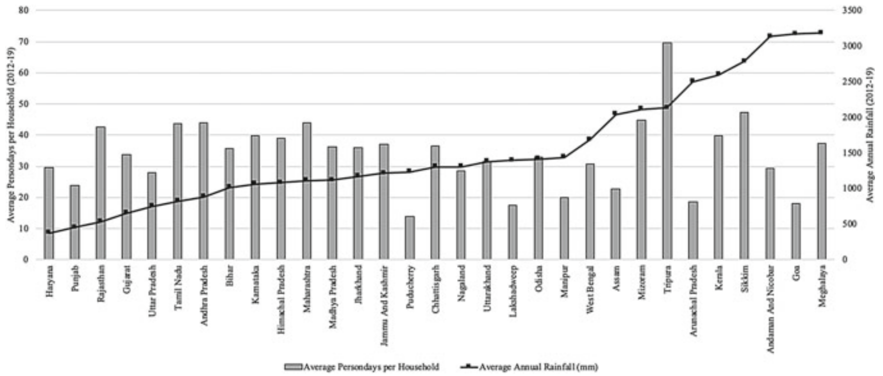

Fig. 3 Average person-days per household generated under MGNREGS against average annual rainfall during 2012–2019

– In states such as Punjab and Haryana, despite having very low average rainfall the demand for MGNREGS works and employment is very low since the irrigation levels and cropping intensity is very high, and these are developed states.

- Majority of the states with low to moderate rainfall have recorded moderate levels of demand for MGNREGS works and employment.
- The northeast states have high level of demand for MGNREGS works and employment in general despite moderate to high rainfall.

Normally, one would expect that the demand for MGNREGS works would be highly correlated to the total rainfall received in a district or a state, assuming that low rainfall and drought would lead to increased demand for MGNREGS works and employment. However, no strong correlation is observed. This may be due to the fact that communities as well as the approving authorities at the district level do not have access to rainfall data of districts at the block and panchayat level. Therefore approval of works and allocation of funds for MGNREGS, or decisions on work selection are not backed by climate information services.

In the near future, fortnightly and weekly forecast of rain at the district level is soon to be available at the block level, which potentially could be accessed and used by communities or the MGNREGS functionaries in scheduling works. Climate change projections at the national and district level show that, generally in most states and districts the rainfall is projected to increase, along with increased frequency of high rainfall intensity events, and in some districts increased rainfall variability. The climate change projections for the short-term (2030s) and the long-term (2050s) at the district level could be used in the following ways to enhance resilience to climate risks, thereby reducing vulnerability and improving adaptation to climate change.

- Selection of works which would be compatible to a flood or drought scenario at the district level.

- Designing MGNREGS assets such as soil water conservation and irrigation to adapt to the projected climatic conditions—such as flooding events or moisture deficit conditions.
- Allocation of funds to districts and fixing of wage rates at the district level based on rainfall and drought/flood projections.
- Tailoring MGNREGS to provide social protection in the context of climate change through adoption of the following principles:
  - Recognise uncertainty in climate and changing frequency and intensity of shocks
  - Avoid maladaptation by taking into consideration climate change projections in planning and design of activities so as to not only foster coping capacity in the short term but also build resilience in the long term.
  - Selection of activities that can address a flood or drought scenario at the district level.
  - Designing assets such as soil water conservation and irrigation to adapt to the projected climatic conditions, such as flooding events or moisture-deficit conditions.
  - Allocation of funds to districts and fixing of wage rates at the district level based on rainfall, drought, and flood projections.
  - Adjust programmes to context as interventions need to be tailored to specific needs and vulnerability contexts. This would be possible only if planning, design, and implementation are science based.

Studies by Godfrey-Wood and Flower (2018) and Adam (2014) have highlighted the need for and potential of mainstreaming adaptation under MGNREGS. However, adoption of the above strategies require a framework for mainstreaming adaptation. In Sect. 5, a generic framework and strategy for mainstreaming adaptation in development programmes such as the MGNREGS is presented.

5 Framework for Mainstreaming Adaptation

There exists a fundamental disconnect between the currently implemented development programmes and climate information in the different states of India, as evident from the analysis of MGNREGS—a programme that is closely linked to NRM, and in its design and intent is to provide employment during lean agricultural period. This underpins the need for dedicated strategies and a framework for mainstreaming.

A framework for mainstreaming climate change adaptation into developmental programmes is illustrated in Fig. 4 with one policy option leading to another in a sequential manner. The analysis and recommendations for each policy option is described below.

Approach and methods for assessing loss and damage due to climatechange: An identification of entry points with which to link climate change adaptation to

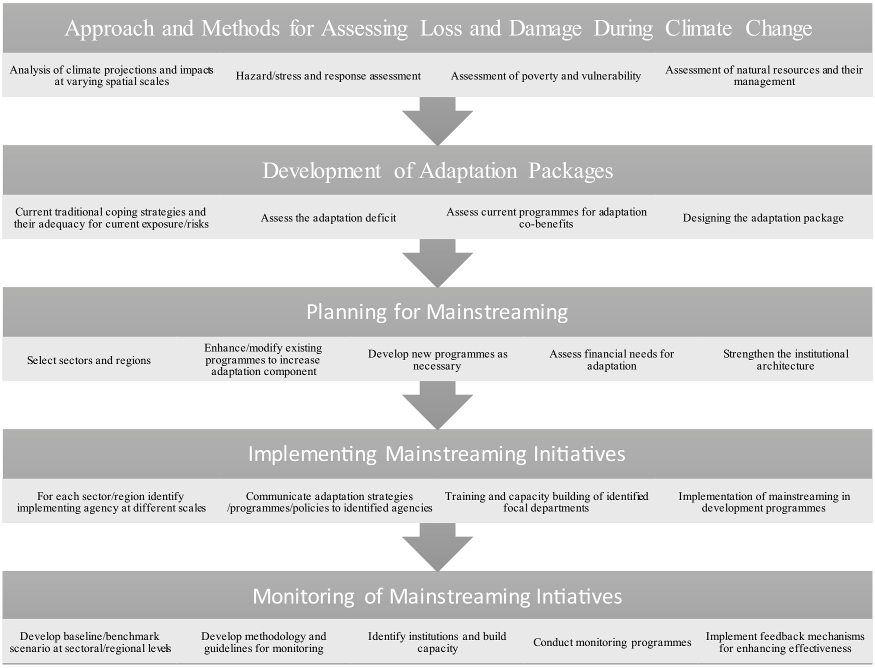

Fig. 4 Proposed framework for mainstreaming adaptation into development programmes

development planning involves submitting the target region under consideration to a variety of assessments at different levels.

– *Analysis of climate projections and impacts at varying spatial scales:* The first step in assessment is an analysis of climate projections at regional and sub-regional levels. Choosing the appropriate models is important for this process so as to avoid errors and minimize uncertainty in downscaling. Additionally, impact analysis needs to be included as a necessary component. It would provide information about biophysical impacts at various spatial and temporal scales and for different convergent sectors such as agriculture, water and forests.
– *Hazard/stress and response assessment:* Hazards tend to be perceived as sudden onset, unexpected, high impact while stresses, on the other hand, refer to smaller, low impact events and seasonal factors. It is necessary to consider this difference in assessment between hazards and stresses, as hazard assessment is more likely to be a measure of the exposure of a system to climate extremes and informs disaster risk management initiatives, while stress responses are likely to be a measure of the exposure of a system to more of non-climatic, political or socio-economic factors.
– *Assessment of poverty and vulnerability:* Poverty contributes to vulnerability. Most development programmes contribute to poverty reduction, and consequently

vulnerability reduction as well, through key policies such as livelihood diversification, sustainable livelihoods, agricultural production or harvesting forest products among others. The livelihood options available locally to individuals and households depend on the diversity of resources, skills and technologies they are able to access. Livelihood options result in reduced vulnerability at individual and household level to the effect of stresses such as climate change by providing income security that is less primarily reliant on natural resources. They contribute to a more positive coping strategy and consequently to increased resilience as well. Livelihood security is tied to an assessment of hazards and stresses as mentioned above, as well as an assessment of natural resources and their management.

– *Assessment of natural resources and their management:* The relationship of the local community with locally available natural resources and their utilization and management is of significant importance. Community participation in NRM is of extreme importance in ensuring its sustainable use. As vulnerability is determined by a gradation of measurement of the access individuals and households have towards the various opportunities to diversify livelihoods from locally available natural resources, it is important to factor its assessment into policy planning.

Development of adaptation packages: Scoping and designing an adaptation package involves ensuring that a programme or scheme or project is well-integrated into the national policy planning and development process and implemented in a systematic manner at varying spatial scales and across different sectors.

– *Current coping strategies and their adequacy for current exposure/risks:* It is important in the analysis of what kind of adaptation measure to include, to determine the current coping strategies that individuals or households use in adapting to climate variability or climate extremes. The nature of these coping strategies—whether they are erosive or positive, reactive or proactive, traditional or innovative—can illuminate whether the adaptive strategies used lead to short-term or long-term change. Building resilience starts with reducing vulnerability and this is where coping strategies used can inform the nature and extent of adaptive capacity inherent in a community in addition to vulnerability reduction efforts.
– *Assess the adaptation deficit:* Addressing adaptation deficit is extremely important as it reveals the gaps and potential draw-backs inherent in certain developmental programmes that may run counter to achieving adaptation to climate change or sustainable development. One reason many of the rural development programmes do not rate high in reducing vulnerability or increasing resilience, is because a large proportion of infrastructure development projects, while offering livelihood diversification options, do not do so in a sustainable manner.
– *Assess current development programmes for adaptation co-benefits:* An assessment of where development programmes rank in the provision of sustainable livelihoods and disaster risk reduction and whether the adaptation co-benefits inherent in the programmes are sufficient or need to be expanded is necessary.
– *Designing the adaptation package:* While adaptation planning is done at a macro-level, adaptation implementation is invariably done at a local level. Development

of sector and region-specific initiatives needs an integration of bottom-up and top-down approaches to implementation. These provide information on the optimal set of policy options that could be factored into a developmental programme's objectives. Converting these objectives into practice entails setting budgetary allocations that cover adaptation components and ensuring that physical targets meet financial expectations. These are key steps to take in designing an adaptation package.

Planning for mainstreaming: Mainstreaming adaptation into developmental programme planning requires a multi-faceted integration of information and institutional infrastructure that entails incorporating climate science, integrating various frameworks to addressing developmental priorities, adopting a multi-disciplinary approach and reflecting the priorities in the financial intentions.

- *Select appropriate sectors and regions:* The selection of the relevant sectors and regions needs to be factored into policy-level planning and programme objectives. There is a lot of differentiation between system characteristics of various regions and there also exists considerable variation in material, institutional and financial resources available to various sectors. It is thus essential to approach modification decisions at a central or state level with a multi-disciplinary lens.
- *Enhance/modify existing programmes to increase the adaptation benefits*: Once the current extent of mainstreaming adaptation as well as any remnant potential has been identified, the programmes need to be modified to enhance the adaptation component in a number of ways. Policy options aimed at reducing vulnerability and increasing resilience almost always rest on a premise of achieving livelihood security for individuals and households targeted in a particular development programme. These policies should also factor in risk reduction to climate variability and extremes as well as ecosystem-based approaches that take into account the importance of natural resource management and ownership by the local communities in order to achieve long-term sustainable development.
- *Develop new programmes as necessary:* There is currently ongoing convergence between different developmental programmes that have similar objectives as well as an integration of current developmental programmes with National Adaptation Mission Interventions. These indicate potential for mainstreaming achievable when new programmes are created with targeted focus on climate adaptation.
- *Assess the financial needs for adaptation:* Once specific policy options have been translated into actionable developmental goals, the disbursement of the budget should reflect the priority accorded to particular adaptation interventions within the developmental programme objectives. Tracking the financial outlay tacked to an adaptation intervention can, over time, be used as a monitoring measure in conjunction with actual physical progress made against the outlay or the expenditure against outlay.
- *Strengthen the institutional architecture:* It is now widely acknowledged that to achieve effective mainstreaming, the complementary but often distinct institutional arrangements that oversee development, disaster management and climate resilience need to be integrated. It is therefore necessary to identify convergence

points between these communities of practice and aim to achieve a level of synergy between them so that adaptation can be mainstreamed across temporal, spatial and functional scales. It may involve a level of cross-sectoral institutional frameworks as mainstreaming adaptation into developmental programmes is by nature a multi-disciplinary initiative.

Implementing mainstreaming initiatives: Implementation of mainstreaming initiatives into developmental programmes is a multi-stage process that involves spatial co-ordination across various levels of government and different sectors. Below a step-wise approach to implementation is presented.

- *Identify the implementing agencies at different scales:* The first step to developing implementation arrangements is to identify key implementing agencies at each spatial scale of implementation as well as across sectors. Coordination of mainstreaming initiatives into developmental programmes is a multi-scalar and multi-sectoral initiative and the governance of implementation needs to be structured in a strong manner.
- *Communicate adaptation strategies/programmes/policies to identified agencies:* Communication of adaptation strategies and policies and methodical guidelines on how these can be mainstreamed into existing or new developmental programmes is necessary. The content, mode and method of communication need to be developed and delivered in a manner that is clearly understandable to all the key personnel involved in the identified implementation agencies. The challenge here is to convey scientific information in a language that is understood by all the stakeholders involved.
- *Training and capacity building of identified focal departments:* Once strategies for mainstreaming adaptation have been communicated and understood by necessary personnel involved, the next step is to build and train the stakeholders in involved agencies on the mechanics of implementation in the sectors and regions under their purview. Training and capacity-building is a necessary step to convert policy to practice. And just as policy development for mainstreaming adaptation into developmental programmes is a cross-sectoral initiative, so too is the delivery of training and capacity-building.
- *Implementation of mainstreaming in development programmes:* Once capacity has been built, the actual implementation of mainstreaming adaptation in developmental programmes takes place. This involves operationalizing planning and implementation via all the arrangements—material, financial and institutional—that have been put into place through the previous steps.

Monitoring of mainstreaming initiatives: Continuity and improvement in mainstreaming adaptation into developmental programmes entails various components that include knowledge sharing among government departments, building community learning processes and investing in monitoring and continuous updating initiatives.

Develop baseline/benchmark at sectoral/regional levels: The first step to monitoring is to establish a baseline or a benchmark scenario that would serve as a point of comparison to measure the progress of implementation of adaptation mainstreaming. These could be a specific year before adaptation became a national priority or a scenario where developmental programmes had priorities that did not necessarily feature adaptation elements.

Develop methodology and guidelines for monitoring: Once a baseline has been developed, the methodology and guidelines for monitoring are required. The methodology for monitoring should include an assessment of how the monitoring architecture would be structured and implemented. The guidelines for monitoring should include the criteria for monitoring and measurement, time scales of recurring monitoring and how resulting assessments and improvements will be taken into account.

Identify institutions and build capacity for monitoring: Following on the methodology for how monitoring would be conducted, an appropriate institutional architecture for monitoring should be developed. Typically monitoring is conducted by organizations or departments that are independent of or not directly involved in implementation. This creates an impartial mode of operation and analysis that is necessary for measuring the extent of and success of mainstreaming.

Conduct monitoring programmes: The deployment of monitoring teams to measure adaptation mainstreaming needs to be conducted at different levels. This would involve due diligence at policy and project levels to assess the extent of mainstreaming policy and planning that has been incorporated into developmental programme objectives at various spatial scales.

Feedback mechanisms for enhancing effectiveness: Finally, the information collected from monitoring and assessment of implementation contributes to valuable feedback on improving mainstreaming initiatives for the future. Therefore, a feedback mechanism needs to be in place to improve the effectiveness of mainstreaming initiatives.

6 Adaptation and Development Nexus

India is at a juncture of development trajectory where there are immense opportunities for development and economic growth. But, there are also multiple challenges due to climate change. Development priorities in India span growth, equity, and sustainability. Climate change is a potential threat to sustainable development. There is therefore a need to integrate climate concerns into all plans for economic growth and socio-economic development. The current barriers and constraints that limit integration of climate concerns and adaptation into development planning revolve around uncertainties associated with climate change impacts. These are the challenges that policy-makers have to grapple with when allocating resources for climate change adaptation.

McGray et al. (2007) refer to mainstreaming adaptation in development programmes as a process that “goes beyond designing projects with a basket of adaptation strategies and their implementation”. It should rather be the fundamental goal so as to address vulnerability. The distinction lies in differentiating between an "adaptation approach" to development and a "vulnerability reduction approach" to development. The latter approach, with its focus on amelioration of conditions that contribute to vulnerability, can be viewed as potentially having supportive complementarities to sustainable development programmes over the long term.

Attempts to integrate adaptation into developmental efforts are constantly plagued by questions of: "what constitutes adaptation to climate change and how is it different from 'good' developmental practices?". It is quite possible that some developmental activities have inherent adaptation components. leading to serendipitous adaptation. There could be some others that have been appended with incremental activities into the original programme design over a period of time, to climate-proof them. However, climate risk screening needs to transition from being a traditional approach of being 'reactive' to a 'proactive' approach that is prepared for an extreme climate event. Such a transition will help build the resilience of systems and communities in the long-term.

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Hydrogen: Towards a Complete Clean Energy Transition and Achieving Carbon Neutrality

Sameer Guduru

Abstract Can hydrogen play the role of being the fuel of the future? Why is hydrogen being looked at closely by the global community? What are the advantages of its adoption? What issues can it likely address being the primary source of energy? What will be its role in the world's clean energy transition? This chapter seeks to answer such questions and discuss various facets related to the use of hydrogen as a fuel. It critically analyses the factors that may impede its wider adoption. Further, the scope for a more combined approach for its cleaner production and the sectors it can revolutionize in the near to long term is also discussed.

Keywords Hydrogen · Photovoltaics · Clean energy · Carbon footprints · Carbon nutrality

1 The Geopolitics of Energy

Energy security is one of the primary drivers of geopolitics. This is precisely what has led to several conflicts in West Asia in the past and even today. Given the nature of existing technologies to produce energy, their dependence on fossil fuels remains immense. Therefore, it has the potential of affecting any country that is externally dependent on energy resources such as India. A significant portion of India's energy basket comprises energy exports from West Asia including crude oil and natural gas. These two commodities are crucial for India to maintain a steady economic trajectory and to feed its population. Hence, the risk of disruption to its energy supply chain with origins in volatile, turbulent, and perennially conflict-laden West Asia looms large on India's policymakers. Thus, there is an immediate need for the country to diversify its energy resources away from fossil fuels in favour of cleaner fuel sources that have low or no (close to zero) carbon emissions. In this context, hydrogen can play a major role with a coherent approach by synergizing efforts from policymakers, energy giants, educational institutions, and industries, etc.

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2 Climate Change and Clean Energy Transition an Inevitability

Hydrogen is the most abundant element in the universe. It is the lightest element with just 1 electron and 1 proton contained in its atoms. It is a vital element associated with life because of its presence in water in the form of a di-hydrogen oxide (H_2O). The stars in the universe primarily are made of hydrogen which fuses at too high solar temperatures and pressure to produce Helium and energy in the process. This fusion reaction goes on and on to create various elements that constitute the universe. However, fission of hydrogen is not the only way to extract energy from hydrogen. It can be used as a fuel in combustion engines and fuel cells to produce electricity. The byproduct of the combustion reaction is water. For decades, this has propelled various researchers, industries, and governments to exploit these advantages of hydrogen as a fuel to drive economies. Hydrogen does not produce carbon emissions and therefore, does not contribute to climate change. As it is widely known today, CO_2 emissions associated with energy account for two-thirds of global greenhouse gas emissions. Hence, it is inevitable to crackdown on carbon emissions and adopt cleaner sources of energy. Renewable energy resources such as solar photovoltaics, and wind energy, have witnessed wider adoption and are today rivalling fossil fuels in terms of power tariffs. However, there remain several factors that eventually impede their broader and faster adoption. For example, in the case of solar photovoltaics, the intermittency period is relatively high as solar panels become ineffective during nights and in bad weather conditions. Moreover, both solar and wind farms need vast tracts of land to establish plants. This assumes even more critical importance in a country like India that is densely populated and is already facing a shortage of land resources.

However, considering countries like India, which is a significant economy and the world's third-largest greenhouse gas emitter, the country has to prioritize her clean energy transition and economic growth simultaneously. This is vital and to achieve a scenario of restricting the average global temperature rise to below 2 degrees Celsius (°C) requires CO_2 emissions to decline by 25% by 2030 from those of 2010 levels and as a broader transition strategy to achieve net zero-emissions by 2070. Countries are also mandated to restrict their carbon emissions to predetermined levels and set targets to combat climate change and its devastating effects. The United Nation mooted Sustainable Development Goals (SDG's) make prescriptions towards clean energy transition. Specifically, SDG #7 focuses on "clean and affordable energy for all", compelling countries, corporations and individuals towards adopting sustainable practices and thereby mitigating the effects of climate change. Given the clean nature of hydrogen fuel with no carbon emissions, the G 20 Karuizawa Innovation Action Plan on Energy Transitions and Global Environment for Sustainable Growth (2019) directs the International Renewable Energy Agency (IRENA) to identify means of achieving a clean energy transition to run economies of scale on hydrogen energy. A joint report prepared by the 2nd Hydrogen Energy Ministerial Meeting and IRENA emphasizes the production of hydrogen from renewable resources of energy, which could eventually propel hydrogen to become more widely adopted and bring down

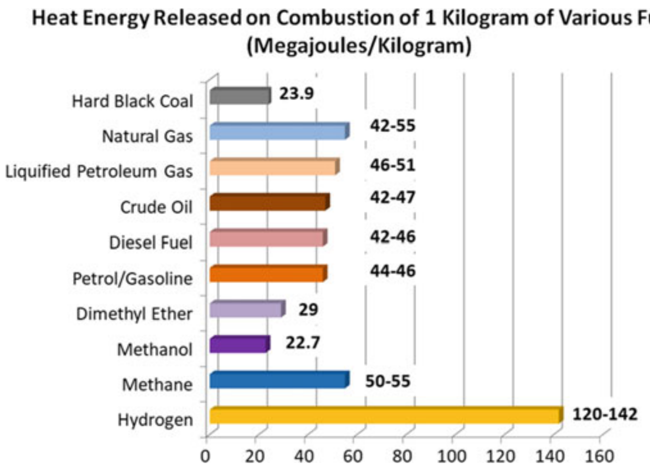

Fig. 1 Comparative Heat-energy produced by burning 1 kg of various fuels [1]

costs significantly and become the fuel of choice in future. The adoption of hydrogen fuel has several inherent advantages that are discussed below (Fig. 1).

3 Advantages of Adopting Hydrogen as a Source of Energy

Hydrogen has the highest energy output (142–120 Megajoules/kilogram), which is almost 2–3 times the energy produced by its closest rival fuel, i.e., methane (55 Megajoules/kilogram). It can either be used in combustion engines or fuel cells or can even be stored to extract energy at any time. It provides an alternative to bulky battery storage that usually employs toxic chemicals to produce electrical power. Such batteries pose a threat to the environment during their disposal and are quite challenging to transport during their lifetimes.

Therefore, hydrogen addresses the issues associated with electricity production and can be utilized for transportation, a sector that needs immediate attention and impetus towards clean transition as almost 98% of this sector runs on fossil fuels. Hydrogen can play a major role in the transportation sector especially in movement of logistics. Its higher energy density and usage in fuel cells makes it ideal for long-haul trucking, railway transportation, shipping and aviation sectors. As battery operated vehicles are restricted in their ranges and battery lifetimes, hydrogen fuel cell powered vehicles are a useful alternative and can play a significant complementary role. Hydrogen in conjunction with other cleaner fuels such as methane in blended form can also be utilized in achieving net carbon neutrality. The carbon released by the combustion of methane can also be captured, and combined with hydrogen, thereby repeating the cycle all over in a carbon neutral manner. Although, carbon capture technologies are still not mature enough for wider adoption. Hydrogen comprises only a small fraction of Earth's atmosphere. Still, it is abundantly accessible in the form of oceans, which form the most significant water source on earth and can be broken down into its constituent elements hydrogen and oxygen in a process known as electrolysis. Hydrogen has the potential to revolutionize heavy industries such as chemicals, iron and steel, heavy metals, and fertilizer industry, etc. The fertilizer industry will benefit immensely as hydrogen can be used as a feedstock to produce methane by combining with carbon dioxide. The methane can then be utilized as a feedstock to produce fertilizers that become essential to feed the developing world where the population is expanding rapidly and global projections of human population reaching 10 billion by the year 2050.

4 Issues with Current Hydrogen Production, Storage Techniques, and Associated Costs

More than 90% of hydrogen produced today, comes from processes that involve fossil fuels. These include techniques like steam reforming, methane oxidation, and coal gasification. These processes usually involve reacting fossil fuels with water or oxygen to produce hydrogen and carbon dioxide. Therefore, these processes themselves intrinsically contribute to the net carbon footprint. Hence, a method of producing hydrogen cleanly without the carbon footprint is a necessity. Since today, the costs per unit of energy from renewables such as solar and wind are competing with fossil fuels. There is a huge scope for adopting an integrated approach. The power generated from wind and solar energy can be used to run the electrolysis of water, and thereby energy can be stored in the form of hydrogen. The electrolysis process is clean and does not have any environmental impact. This form of hydrogen produced from fossil fuels is termed as green hydrogen. Since the oceans are the most abundant water source, they can be treated, and electrolysis can be performed to produce hydrogen. Even though this sounds possible, several constraints persist. Hydrogen is the lightest gas and therefore, its storage requires it to be liquefied or kept under pressure or converted into toluene or ammonia for its transportation. The liquefaction of hydrogen occurs at shallow temperatures of −250 °C. This process of liquefaction also consumes energy. Moreover, the conversion of hydrogen into other forms such as toluene or ammonia, also expends energy. So, the overall energy output falls down to just 30% of the actual energy that hydrogen produces. In addition, as of today, 70% of the cost of green hydrogen are the costs of power utilized to produce it (Fig. 2).

These factors naturally have a bearing on the end-price of hydrogen and have to be factored when comparing other renewable sources of energy. This is quantified

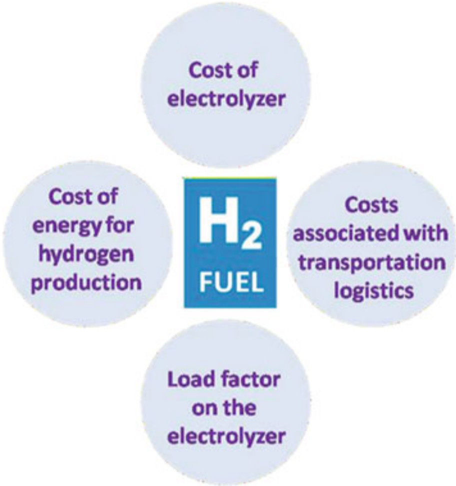

Fig. 2 Factors contributing to the overall cost of hydrogen [1]

in the form of comparing the "Levelized Cost of Energy" (LCOE).[1] According to IRENA, to achieve parity and to compete with other forms of energy sources such as fossil fuels, the LCOE of hydrogen production from renewables should be under US$ 2.5/kg. The IRENA report of 2019 analysed two different power tariff scenarios of producing hydrogen from renewable wind energy. The first being a "*relatively low cost*" scenario (power tariff of US$ 40/MWh), and the second, a "*very low cost*" scenario (power tariff of US$ 20/MWh). The study also took into account the current and the projected future price of electrolyzers at US$ 840/kW and US$ 200/kW, respectively. The conclusion was that the production of hydrogen from renewables in these scenarios cannot compete with the production of hydrogen from traditional methods such as methane reformation (US$ 5 per gigajoule, i.e., 1.8 US cents/kW). However, hydrogen production from renewables can compete with natural gas prices when applied in large-scale industrial applications, where the costs are USD 10/16 per gigajoule.

Nonetheless, with expected improvements in technology and increasing electrolyzer efficiency as well as capacity and load factors and the consequent price-reduction, the cost of producing hydrogen from renewables will witness a decline. Also, taxation on carbon and carbon credits will hasten industries towards a transition in the direction of hydrogen. The report finally concludes that the price of green renewable hydrogen will start competing with traditional production methods by 2035 and, in an ideal scenario, might overtake the next few years.

[1] LCOE measures lifetime-costs divided by energy-production. It calculates the present value of the total cost of building and operating a power plant over an assumed lifetime. It thus allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities. As such, it is critical to making an informed decision to proceed with development of a facility, community or commercial-scale project.

5 Hydrogen Production from Renewables Sources of Energy: A "Hybrid" Approach

(a) Hydrogen from Solar Photovoltaics

Over the last few years, solar photovoltaics have witnessed tremendous growth. This is primarily because countries like India and China have adopted solar photovoltaics in a big way to enable their clean energy transition. Both the countries host some of the world's largest solar parks in terms of area and capacity. This has driven a solar boom of sorts with the establishment of the International Solar Alliance jointly founded by France and India post the Paris 2015 climate talks. Given this widespread adoption, including rooftop solar and subsidies by the government, the prices of solar power per unit today are less than or at par with fossil fuels.

Moreover, since issues related to land occupation persist, floating solar plants are becoming increasingly popular. Solar panels that float on the surface of water bodies and thereby do not occupy land while at the same time also save the water from getting evaporated from urban catchment reservoirs. Similar floating plants are now being implemented on oceans' also to produce electricity to be utilized by coastal communities and establishments. Considering the proximity of such plants to water, which can be broken down into its constituent elements via electrolysis, combined approaches for producing hydrogen from solar photovoltaics has been proposed. The electrolyzers will be installed either onshore or offshore and will be powered by solar photovoltaics to harness hydrogen cleanly without any carbon footprint. These techniques are increasingly being termed as innovative ideas towards establishing localized hydrogen production plants, thereby bypassing its transportation and associated difficulties such as its liquefaction and conversion into other materials such as Ammonia. Moreover, the hazards of transporting hydrogen under pressure are reduced, and so is the risk of explosion and leakage (Fig. 3).

(b) Hydrogen from onshore/offshore wind power

Similar to the earlier techniques, hydrogen production plants in conjunction with onshore and offshore wind energy plants are being implemented. In this case, wind power drives the electrolysis and the production of hydrogen. The German city of Hamburg, for example, has already demonstrated the use of offshore wind energy to produce hydrogen. Hydrogen produced especially from offshore wind energy has several advantages due to its proximity to coastal areas. It can be utilized for the energy transition of the shipping and the aviation sectors, which are some of the world's biggest carbon producers. Moreover, providing auxiliary power to berthed ships in what is called as "cold ironing" becomes possible with hydrogen-powered fuel cells. This reduces emissions from vessels berthed at ports as ships typically have their engines running even at ports to power loading and unloading processes and other onboard activities. This will also reduce Sulphur Oxide (Sox) emissions, following the MARPOL Annex VI of the International Convention for the Prevention of Pollution from Ships, (1973), which mandates ships to run on less than 0.5% of sulphur content in the fuel, beginning January 2020.

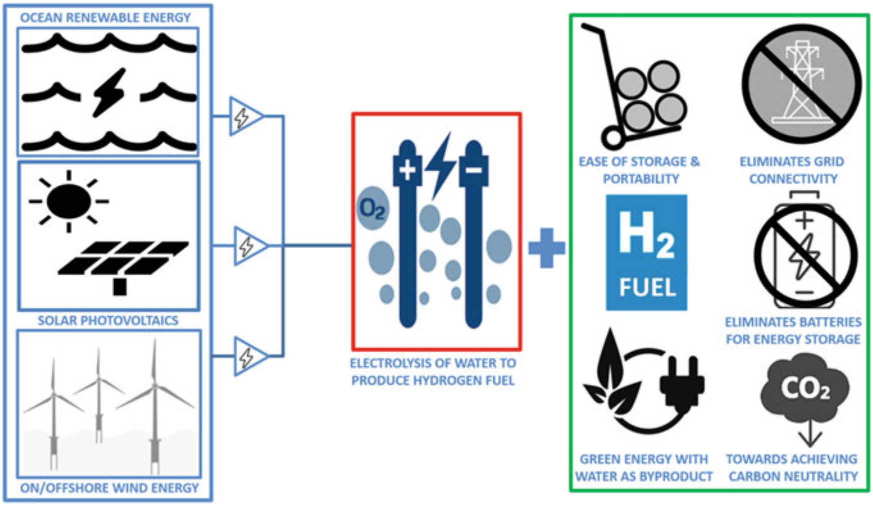

Fig. 3 Hydrogen production via a combined generation process. Power from renewables is used to run electrolysis of water and to produce hydrogen. *Source* Created by Dr. Sameer Guduru

(c) Hydrogen from other forms of renewable energy

Other sources of renewable energy, including Ocean Wave-Energy Conversion (OWEC) for hydrogen production in a combined manner, have also been proposed. Ocean Wave Energy is a continuous source of energy, and when combined with hydrogen production using electrolysis, it can play a much larger role. Studies conducted in the Italian islands of Sicily and Pantelleria, conclude that this approach can significantly reduce carbon emissions. Similarly, another form of ocean energy called the Ocean Thermal Energy Conversion that produces electricity, works on the temperature gradient existing between cold deep seawater and the warm surface seawater. Ideally for achieving higher efficiency of this process, the temperature difference should be 20 degree Celsius, as this difference is enough under the right pressure conditions to evaporate liquids like Ammonia that drive turbines and produce electricity. Such offshore OTEC plants can also be proposed to produce hydrogen via the electrolysis of seawater (Fig. 4). Apart from ocean energy resources, hydroelectric dams are also being employed in hydrogen production. Power from hydropower plants will be utilized for electrolysis of water and such projects are gaining adoption in countries such as Canada, in the form of a 88 MW electrolysis plant in Varennes, Quebec.

6 Hydrogen as a Fuel in Various Sectors

(a) Hydrogen in Shipping

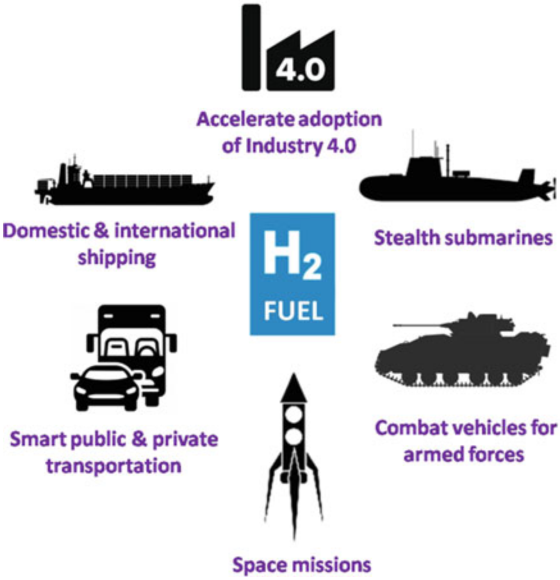

Fig. 4 Sectors to be positively impacted by Hydrogen Fuel [2]

Shipping based on hydrogen fuel is the next logical step and plans are currently afoot in Norway, the United States, Switzerland, and France. NORLED and WESTCON in Norway are working together on the world's first hydrogen-fuelled car ferry. Commuter ferries powered by hydrogen are being developed in the San Francisco Bay Area of California, by New York-based SW/TCH (pronounced Switch). Swiss ABB, and *Hydrogène de France* are manufacturing megawatt-scale hydrogen fuel cell systems to power ocean-going vessels. Considering the issues related to hydrogen transportation and storage, offshore hydrogen fueling stations are regarded to hold some promise, because as such, the large ocean-going vessels do not have to enter and exit ports for refuelling which might otherwise take a longer time. This is possible due to the emergence and development of new approaches to produce green hydrogen. Countries like India have launched ambitious projects such as the Sagarmala Project that focus on port-led connectivity, and the opportunities are immense. Given the sensitivity of riverine ecosystems to engine noise and marine pollution, hydrogen usage in inland waterways can have a revolutionary effect. This will first bring down pollution from the trucks by shifting the demand to inland ships and waterways for bulk quantities and reducing pollution from inland shipping, which usually traverse hinterland areas that are away from both air and noise pollution. The coastal/ marine tourism sector can also benefit immensely with the adoption of hydrogen as a fuel in passenger ferries and cruise liners.

(b) **Hydrogen in Military Applications/ Autonomous Platforms**

Off late, unmanned platforms are increasingly becoming common in military applications. They are being used for logistics transportation, in combat, surveillance, underwater mapping, for reconnaissance missions, etc. Since the platforms are autonomous, they minimize the number of mortalities in combat and are of particularly interest. Unmanned surface vessels (USV), unmanned underwater vehicles (UUV) platforms, and unmanned aviation vehicles (UAV) are being widely adopted in research as well as military applications. Given hydrogen and the advantages it offers, long-endurance UUV's have already been demonstrated. Such platforms have the added benefits of stealth due to low noise generated in producing energy, long endurance times. This helps in having a long and extended period of deployment at sea while gathering scientific data or in anti-submarine warfare applications.

Moreover, with seabed mining prospects increasing rapidly, considering the abundance of mineral resources, both tethered and untethered remotely operated vehicles (ROV's) are being developed, which can be fueled by hydrogen. Both naval surface platforms, as well as underwater platforms, are adopting hydrogen fuel. Naval platforms, just like their commercial counterparts, have large carbon emissions at berths by guzzling away large amounts of fossil fuels. One of the remedies is to use hydrogen to propel these ships than gasoline or diesel. They can also be powered using auxiliary power provided at the port facility, which itself can be hydrogen-based.

The German Navy and the Italian Navy currently operate the Type 212A Class, air-independent propulsion (AIP) submarine powered by Proton-Exchange Membrane (PEM) hydrogen fuel cells with a higher endurance level. They can remain submerged for operation periods up to three weeks without the need to surface, unlike their diesel-electric submarine counterparts which have to surface every few hours to recharg their batteries, therefore vulnerable to be spotted by rival navies. They have also customized for stealth applications due to reduced noise levels from the engines. These submarines can remain undetected with nonmagnetic components and can reach very close to coastlines with just 17 m depth. The US army has its surface combatant vehicles like tanks, artillery, etc. which are slowly employing hydrogen fuel cells due to reduced noise levels and, therefore, offering the enemy's prospects from close quarters. Due to the propulsion systems working on power generated from fuel cells instead of combustion engines, the thermal signature is also reduced and thereby the chance of getting detected.

(c) **Hydrogen in Aviation**

While demonstrations of flights powered by hydrogen fuel cells have been successfully developed in countries like Germany, the application of hydrogen in air transportation is still in its very nascent stages. The world's first six-seater passenger plane fueled by hydrogen was demonstrated in September 2020 in the United Kingdom. Aviation is a sector that has a considerable carbon footprint, and the industry can benefit immensely by getting rid of fossil fuels such as jet kerosene. Several challenges such as scaling up, hydrogen storage onboard, etc., have yet to be achieved before a full-scale demonstration of passenger and cargo aviation powered by hydrogen can be demonstrated and given the current investment and research and development in the area, the day is soon. In fact, Airbus is currently working on realizing its first hydrogen powered zero emission aircraft named ZEROe. Such innovations will likely play a major role in reducing carbon emissions of the aviation sector that is expanding rapidly in emerging economies like India.

(d) **Hydrogen in Road and Rail Transportation**

With the emergence of smart vehicles, the electric vehicle (EV) segment today is divided between battery-operated EVs and fuel cell-operated EVs. Public transportation such as buses and private cars like cabs driven by hydrogen are slowly finding space in the market. This is primarily because the time taken to recharge battery-operated vehicles takes a few hours compared to EV's run on fuel cells, which can be filled with hydrogen and oxygen in a few minutes. Hydrogen-driven trucks and other vehicles used in logistics are increasingly being adopted across countries including Germany, Netherlands, Canada, Chile, New Zealand, Japan, Korea, France etc. In the case of rail transportation, Coradia iLint is currently being operated in Germany and was developed by Alstom as the world's first commuter train run on hydrogen. India is also currently working on realizing hydrogen propelled locomotives to eliminate diesel-powered locomotives to reduce emissions in a phased manner.

(e) **Hydrogen in Space Applications**

Outer space is not immune to international politics either. Space is increasingly becoming relevant from a geopolitical and strategic perspective with the increased weaponization of space. The near future will undoubtedly witness the deployment of weapons in space. This requires platforms such as heavy rockets propelled by a mix of different fuels including hydrogen, oxygen, and methane, etc. With high calorific value and the prospect of creating methane by reacting with carbon dioxide in an in-situ process, rocket propulsion relies heavily on hydrogen as a fuel.

(f) **Hydrogen Powering Industry 4.0**

Emerging technologies such as artificial intelligence, the internet of things, 5G, etc., are reckoned to be the future technologies. With the availability of electric propulsion of the transportation sector, the prospects of adopting emerging technologies such as AI, 5G, IoT, Virtual/Augmented Reality become a possibility. Increasingly, the shipping sector is getting automated and similarly does the EV segment of the market. Such vessels carry onboard sensors that assist in navigation with concise latency periods and instant feedback mechanisms.

7 Conclusion

Energy commodity vulnerabilities from volatile source regions of energy and climate action targets have compelled the world to pay more attention to run economies of scale propelled on hydrogen power. Even though the transition is rather slow, considering the hydrogen-based technologies are relatively new and need time to attain market maturity. This, however, is likely to change quickly soon with the increased global impetus on developing efficient hydrogen production technologies and its wider adoption across the industry. Hydrogen perhaps offers the best hope for humanity to achieve carbon neutrality by the year 2070 and thereby mitigate climate change. Due to its inherent carbon footprints, hydrogen production, when achieved from fossil fuel-based sources, needs an alternative carbon-free approach today. This is becoming a reality by adopting a combined approach from solar photovoltaics, wind energy, and other renewable energy forms. The power from these platforms is utilized to drive electrolysis of water and thereby produce hydrogen. The hydrogen thus obtained is termed as *green hydrogen*. Hydrogen has varied applications in the transportation sector both when used in mixed fuels as well as in the form of fuel cells. Also, the armed forces' combat platforms are increasingly relying on hydrogen for the prospects of stealth and more extended endurance period in the form of UUV's, UAV's, USV's, and even submarines. Hydrogen can also revolutionize the aviation, road, and rail transport sector and transportation along inland waterways. Also, the prospects offered in terms of excessive power can efficiently be utilized to further the adoption of emerging technologies such as AI, IoT, etc., and thereby accelerate these industries' development. In short, hydrogen can become the fuel of future and address the issues related to climate change via decarbonization and eventually net carbon neutrality.

Note: The study on hydrogen as a prospective fuel was carried out at the National Maritime Foundation, New Delhi.

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Climate Change and Politics

Mohd. Yousuf Bhat

Abstract Climate change is becoming prominent in mainstream politics. Liberal governments have generally learnt into the narratives of climate action, claiming it as a priority, while consistently failing to make significant progress towards just transition, adaptation, and associated economic transformations. Eco-fascism is said to be looking, but actually existing far-right. Governments have tended towards a more steadfast solidarity with fossil capital. They have not demonstrated a willingness to break with capitalist economies which produce the climate crisis. Within liberal democracies, left-wing and socialist parties have demonstrated the strongest commitment to programs of economic transformation, most commensurate with the scale and nature of the climate crisis. Whether Bernie Sanders' Presidential campaign in the US, Jeremy Corbyn's election campaigns as leader of the UK Labour Party, or Jean-Luc Mélenchon's campaign for President with La France Insoumise, these climate justice socialists have rarely taken state power. While China's geopolitical rise may pose a challenge to the US' geopolitical hegemony, possibly even including its brand of capitalism, there is little evidence that China's rise will be any better for the climate in the coming decades. At the same time as investing in renewable technologies at home, China is financing new coal power and mines across Asia and Africa. Where other political formations have neglected climate change, Green parties around the world have sought to establish themselves as the electoral vehicles for environmentalism. Like their ideological orientation, their success has been inconsistent. Lacking strong ideological commitments, Greens have often allied with neoliberal or even far-right governments in exchange for proximity to state power.

Keywords Climate politics · Neoliberals · Green ideologies · Green slogans · Eco-feminism · Environmentalism

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1 Introduction

Climate Change is considered as the mother of all problems. It is a crucial issue of contemporary times with population growth on one side and fulfilling its needs on the other hand. With the rising temperatures, apocalyptic events will unfold in future and that will be a phase of human race where there will be no returning to the earlier world. United Nations points out the severity of global warming through its report which reads, "quantities of greenhouse gases in atmosphere have risen to record levels not seen in three million years. As populations, economies and living standards grow, so does the cumulative level of GHG (greenhouse gas) emissions". In the planet's climate there is a clear correlation between the carbon dioxide, methane and nitrous oxide level and the "greenhouse effect" which is gradually warming the mean temperature of the globe (Irwin 2008a). Human fingerprints on climate indicate that the environment is severely strained by the pollution from modern industrial processes and the lifestyle of consumerism. With the start-up of 1750's Industrial Revolution, levels of carbon dioxide started rising steadily from the "natural background" levels of less than 280 ppmv to over 370 ppmv and the same sudden jump can be seen for methane and nitrous oxide (Irwin 2008b).

The complex politics of global warming results from dependence of economic activities on fossil fuels (responsible for Carbon dioxide) and agriculture and land-use change (responsible for methane and nitrous oxide). The primary mechanism of tackling this global warming is through Paris Agreement that replaced Kyoto Protocol in the year 2020, both established under United Nations Framework Convention on Climate Change (UNFCCC). Although Paris Agreement focuses on all countries to tackle climate change unlike that of Kyoto Protocol which applied top-down approach and targeted only historical emitters. But it again leaves space for emerging economies to continue emitting until they feel of having done enough. Once a country formally joins the agreement there are no specific requirements about how and how much countries should cut the emissions. Consequently, national plans also vary critically in their aspiration, mainly reflecting each country's capabilities, their level of development and contribution to emissions over time. China for example committed to levelling off its carbon emissions no later than 2030 and reducing carbon emissions per unit of gross domestic product (GDP) by 60–65% from 2005 levels by 2030. India set its vision on cutting down the emissions intensity by 33–35% below 2005 levels and producing 40% of its electricity from non-fossil fuel sources by 2030 (Denchak 2018).

These gases have a strong detrimental impact on global ecosystem, more importantly in developing and least developing nations. On a larger canvas, these countries have many internal and external challenges. Internal in the sense to reduce poverty, provide employment to their people, to increase living standards and external challenges like meeting out trade targets with other nations. Consequently, such demands put a lot of pressure on natural resources and adoption of technologies which are not environment friendly and thereby increase greenhouse gas emissions. The other reason is that with the start of globalization a homogenous global culture has taken place. People with traditional heritage revolving round the environmental preservation, they carried for generations got diminished by culture of consumerism. This new culture of consumerism has generated artificial demand of goods and consequently pressure on natural resources and unforeseeable impact on climate.

Looking at Syrian conflict from the angle of climate change, analysts admit that there were multiple causes of Syrian civil war that began in 2014. Marwa Daoudy, while writing on Climate Change and Human Security mentions that Syria has suffered devastating consequences of climate change, but these consequences and the seeds of their discontent are not solely due to climate stress. They can be found in a quagmire of political, economic, social and environmental vulnerabilities that impacted Syria's most vulnerable population for decades before the 2011 uprisings (Daoudy 2020). The data gathered by scientists shows that severe water shortages in Syria, Iraq and Turkey killed livestock, shooting up of food prices, and sickened children resulting in a mass migration of 1.5 million rural residents to Syria's densely packed cities at precisely the same time as that country was exploding with immigrants from Iraq (Simon et al. 2019).

Climate change is a potential risk to human security and unfortunately the international community has not anticipated its associated risk to peace and security, e.g., neither UNFCCC nor the Kyoto Protocol contains any reference to human security. However, the impact of climate change on peace and security has only been deliberated in a few instances at UN Security level, that held its first-ever debate in 2007 vis-à-vis the impacts of climate change on peace and security (UN Press Release 2007). This debate was initiated by United Kingdom and supported by small island states. However, many developing countries like India and China felt that the Security Council was not an appropriate platform to discuss the issue (The Guardian, April 8, 2007). On the other occasion in 2011, Ban Ki-moon (the then Secretary-General of UN) stated in the security council session that "climate change not only aggravates threats to peace and security, but is actually a threat to the peace and security" (UN press release 2011). However, this session leads to the conclusion that the UNFCCC is the primary forum for addressing and discussing climate change, but also noted that "conflict analysis" on the "possible security implications of climate change" is vital once climate problems drive conflicts, challenge implementation of Security Council mandates or endanger peace processes (UN Press release 2011). If we look at politics of arms race, there is a huge arms industry and a huge arms procurement, particularly by developing countries. Due to this mad rat race for arms procurement the climate issues always become the secondary concerns. Climate induced conflicts can be avoided if big powers and their arms industries show some inclination towards addressing developmental and climate concerns of developing and least developing countries.

It is understood that climate change will overstress many societies adaptive capacities within the coming decades. This may result in violence and destabilization, consequently, jeopardizing national and international security. Nevertheless, there is a hope that climate change could unite the international community, if nation-states recognize climate change as a threat to humankind and soon set a dynamic and globally coordinated climate policy to avoid its devastating impacts. If it fails to do so, climate change will draw ever-deeper lines of division and conflict in international relations (German Advisory Council on Global Change, World in Transition).

2 Climate Problem and Politics of Global Economy

The Human Development Report of 2013, highlights that economic growth alone does not automatically translate into human development progress. The pressing challenges before humanity are the issues like poverty eradication, climate change and peace and security and the report stresses on a coordinated action to meet out these challenges (Human Development Report 2013). However, the challenge before us is that the ideology of neoliberalism (often bracketed under the heading of the "Washington Consensus) with its emphasis upon the role of free trade and markets and restructuring of the state (Wilkin 2001). This ideology has now become a challenge, as the changes it brought with it are inconsistent with human security. Industrialized countries were mostly benefited by this ideology as they employed it to gain their economic interests at the cost of the developing world. Today in the global politics territorial expansion is a risky job, rather economic development and trade are now given preferences by industrialized and developed nations. This new mechanism through the ideology of Neoliberalism has helped industrialized countries in exploiting the resources of developing countries thus bringing in more gaps between the rich and poor nations, and putting a huge pressure on the resources of poor and developing nations.

Third world countries are at the bottom of the global economic hierarchy because of the multiple problems like poverty, hunger, healthcare, broken infrastructure, lack of money, resources and, access to information. Keeping in view the despicable situation of these countries, the Neo-Marxists argued that the global capitalist economy controlled by wealthy capitalist states is used to impoverish the world's poor countries. These theorists argued that free trade and international market relations occur in framework of uneven relations between developed and underdeveloped countries and work to reinforce and reproduce these relations.

Capitalists, however have a different perspective, as they saw in the philosophy of neoliberalism an opportunity to free themselves from regulations and taxes. Francis Fukuyama, a traditionalist, strongly criticizes the neoliberal policies imposed by the United States on less developed countries, particularly in Africa. He showed, how such policies failed states (Bresser 2009). This neoliberal ideology helped rich countries to take control over week states that allowed national economies of week states to become a playing field for large corporations, their top executives and financial agents to obtain all kinds of rents—in lieu of moderate interest rates, fair business profits and professional wages, of the economic elites (Ibid). International financial institutions such as IMF and World Bank appear to have strengthened the interests of MNCs (multinational corporations) and international financial capital, rather than a long-term commitment to democracy and prosperity in the developing countries. For example, India's external debt crisis of 1991 brought the country close to default in meeting its international payment obligations and under such challenging situations India also adopted neoliberal or in other words “market-friendly” economic policies (Siddiqui 2010). In India on embracing the ideology of neoliberalism was accompanied by a change in the position of big bourgeoisie. The Indian bourgeoisie since 1991 economic liberalization got increasingly integrated with the international financial capital and pursued strategic alliances with western capital (Wolf 2006). The paradox is that on the one hand corporate “friendly” government policies have provided tax concessions of around $75 million between 2015 and 2016 (Peoples voice 2015), but on the other hand, thousands of farmers are trapped in the cycle of debt and poverty and are thus taking their lives. What is more shocking is that 3 lac plus farmers have committed suicide between 1995 and 2015 as per records of India’s National Crime Records Bureau (Salam 2018). But in the whole scenario, where their deaths can be related to poverty or unfriendly government policies, the climate change footprints can also not be ruled out. Research points out that India has already become third largest emitter of greenhouse gases after China and United States (Sen 2020). It emitted around 2,299 million tonnes of carbon dioxide in 2018, as per the reports of the International Energy Agency, accounting for 7% of the global greenhouse gas emissions (Ibid).

The United States is the leading producer of carbon dioxide, and China is quickly catching up. Many nations in the developing world are also expanding their output considerably and these dynamics present a twin problem. First, the high-producers have economies that heavily depend on fossil-fuel consumption. Next, the developing nations resent pressures placed on them by the developed nations to restrict carbon emissions, in full recognition that these older economies were built and enriched by burning petroleum, coal and other fossil fuels (Haas and Hired 2013). In developing world population growth is in tandem with their rising economies. The consumer lifestyle of the middle class of these countries like India and China is akin to those of developed countries like USA. Thus, twin impacts of rising populations and growing economies produce a stronger incentive to continue to produce greenhouse gases. These are the powerful incentives to overcome, and international institutions lack the enforcement capabilities to compel behavioural changes. The challenge with respect to developing nations is to dissociate economic growth from emissions and to encourage developing nations to adopt cleaner and new green technologies. (Ibid).

3 Universal Initiatives on Climate Change

To ensure universal participation in controlling climate change, a number of initiatives have been taken and among them some important ones are Stockholm Conference, Rio Summits, Kyoto Protocol and Paris Agreement. Mitigation of adverse impacts of climate change started with the 1972 Stockholm Conference popularly known as United Nations Conference on Human Environment (UNCHE). This was the first step in which linkages between economic growth and environmental consequences were accepted. The recommendations of the conference were disregarded by industrialized nations, but it made sufficient impact in motivating United Nations to establish the United Nations Environment Programme (Maikasuwa 2013).

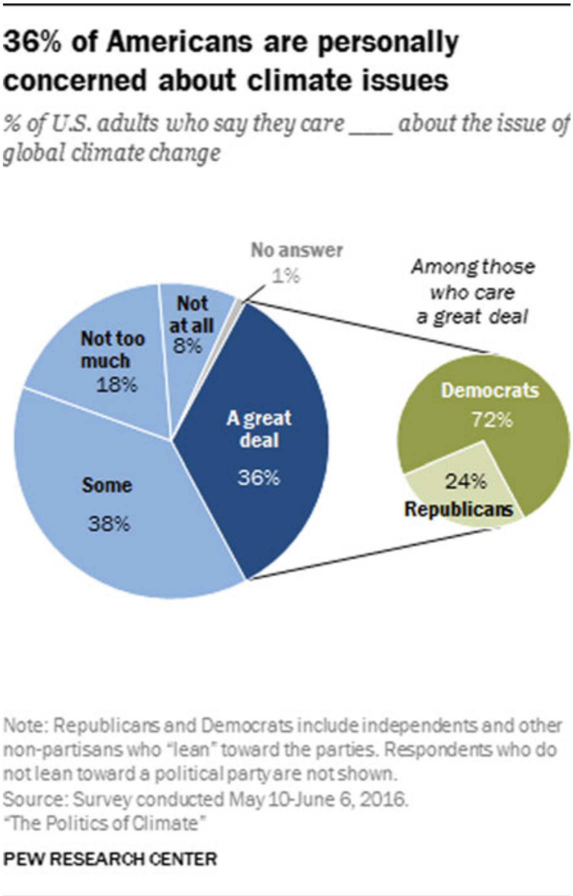
It took another 20 years to the international community for convening United Nations Conference on Environment and Development at Rio de Janeiro in 1992, the outcome of which gave us the United Nations Framework Convention on Climate Change (UNFCCC). The objective of UNFCCC was to stabilize greenhouse gas concentrations into the atmosphere. But it has not been effective enough in catalysing mitigation action to match the below 2-degree trajectory as its historical focus on emission targets has been too narrow. Kyoto Protocol as the first extension to UNFCCC was signed in 1997 but entered into force in 2005 with ratification of 55 states of Annex 1 signatories that together accounted for at least 55% of total carbon emission at 1990 level. The Protocol committed its signatories to develop national plans to reduce greenhouse gas emissions. As the Protocol is based on the principle of common but differentiated responsibilities recognising the different capabilities of individual countries it puts more responsibilities on developed nations to take a lead in cutting down the emissions. Under the Protocol, Clean Development Mechanism (CDM) was established which aimed at reduction of GHGs to support sustainable development. In CDM developed countries were to invest in low cost abatement opportunities in developing countries and also gave incentives to private sector to invest in GHG-reducing projects (Zhang and Maruyama 2001). However, global emissions had risen during Kyoto Period as United States and China were major contributors of GHGs to erase all reductions made by other countries with exceptions of some countries and EU who were on track by 2011 to meet and exceed their Kyoto goals (The Guardian, 11 March 2011). The succeeding summits were Earth Summit II (2002) popularly known as Rio + 10, which discussed sustainable development and reaffirmation of commitment by world leaders to work towards sustainable development. The subsequent Johannesburg summit was tall on setting new targets but again there was little or no success in reduction of GHGs (O'brien and Willians 2007). Rio + 20 convened in 2012, to further assess the progress made in sustainable development called for a wide range of actions for attaining sustainable development which are (i) how green economies can act as the tools to achieve sustainable development (ii) developing strategy for sustainable development financing (iii) adopting framework for sustainable production and consumption and (iv) focusing on gender equity as well as incorporating science into policy and involving civil society in mitigating consequences of climate change. However, what is apparent, that nothing concrete has been done to change the existing framework that weakens the capacities of developing countries to put in place policies for sustainable development of their societies (Maikasuwa 2013). These summits were again superseded by Paris Agreement of 2015, which entered into force in 2016. This was the landmark agreement aimed to combat climate change and accelerate all efforts for low carbon future. The central concern of Paris Agreement was to strengthen global response to the common threat of climate change by bringing all nations into common cause to undertake ambitious efforts to combat climate change. It calls upon all nations to keep the global temperature rise of this century 2 degree centigrade below the pre-industrial levels. As of year, 2019, there were 189 countries that ratified the Paris Agreement with the exception of only few major emitting countries like Russia, Turkey, and Iran. The United States of America ratified the agreement in 2019, but within a short span of time in same year took a decision to withdraw from the Agreement effective from 4th November 2020 in accordance to article 28 (1) and (2) of the Agreement (Paris Agreement-status of ratification UNFCCC).

4 Challenges to Universal Participation

In achieving the goal of global participation there were certain hiccups particularly the U.S. position has remained quite paradoxical on climate change negotiations from 1985 to the present. In the late 1980s, United States advocated for universal participation but latter rejected it by withdrawing from the Kyoto agreement in 2001. That Kyoto agreement has been repudiated by President Bush, who has called it "fatally flawed," saying it places too much of the clean-up burden on industrial countries and would be too costly to the American economy (New York Times, 24 July 2001).

In the cold war era, under the Bush Administration, the American Federal Government refused to engage with the scientific data about climate warming or the global political pressure to reduce their greenhouse gas emissions. The lack of commitment from leadership from a historically powerful State has given room to other nations to publicly or quietly fail to enforce the Kyoto objectives for reducing greenhouse gas emissions to the levels of 1990 or preferably lower (Irwin 2008a, b). Under Obama administration, USA again entered into Paris Agreement in 2016; however, Donald Trump on 1 June 2017 made an announcement of ceasing all participation in Paris Agreement, with a condition that we are willing to enter into any agreement only "on terms that are fair to the United States, its businesses, its workers, its people, its taxpayers" (Chakraborty 2017). His statement was based on America First Policy and he was of the opinion that this climate agreement will undermine economic interests of USA and will put America at a permanent disadvantage (BBC News, June 1, 2017).

According to Pew Research Center which is a nonpartisan fact tank that informs the public about the issues, attitudes and trends shaping the world, observe that Liberal Democrats and Conservative Republicans see climate-related matters through vastly different lenses. Their observation is that Liberal Democrats are more inclined to environmental issues like Obama's entry into Paris Agreement and now President Joe's intention to re-enter into Paris Climate Agreement. The Pew Centre finds that Republicans are more sceptical about research findings of climate Scientists' and their information and understanding on climate change (Pew Research 2016). This observation gives us a very disturbing impression of inconsistent public policy of USA towards Climate change as we usually have alternative governments in American elections.



Lastly, the literature on environmental politics, global governance, and international relations has paid less attention to questions of participation. If we want to search for issues of global warming and climate change, we usually find them in last chapters of books written on international relations and global politics. Indian novelist, Amitav Ghosh in an interesting book entitled "The Great Derangement: Climate Change and the Unthinkable," writes that climate change is even more absent in the world of fiction than it is in nonfiction.

5 Developed Versus Developing Nations

Intergovernmental Panel on Climate Change (IPCC) highlights that poorer nations are extremely vulnerable to disasters and hence to the effects of climate change for a number of reasons. First, the ability to adapt and cope with weather hazards depends on economic resources, infrastructure, technology and social safety nets. (IPCC 1995). Developing countries often do not have the resources and are thus ill-prepared in terms of coastal protection, early warning, disaster response systems and victim relief and recovery assistance (GEF 2001). Secondly, many developing countries are already under pressure from population growth, rapid urbanization and resource depletion, making them further vulnerable when these challenges are coupled with the problem of climate change (IPCC 2001; Jepma et al. 1996).

There is too much apprehension among the developing countries who are lagging in the technological advancement and most importantly if they have the resolve to work for climate change, their economies don't allow them to do so. The bone of contention between developed and developing countries is that who is going to pay for reducing greenhouse gas emissions. It is recognized under UNFCCC that implementation of commitments by developing countries will depend on financial and technical assistance from the rich nations (Winkler 2005). The concern of developing countries is historical in nature, "In Madrid Climate change Conference, the key polluting countries accountable for 80% of the world's greenhouse gas emissions stood mute, while smaller countries announced that they will work to drive down harmful emissions in the coming years," Natural Resources Defense Council-a US based climate action advocacy group observed that "World leaders dithered instead of taking stronger, critical action soon to reduce the global climate threat. They ignored dire scientific reports, worsening evidence of climate destruction and demands from millions of young people to protect their future" (Dettmer 2019).

Climate change is a staggering problem for all countries that need costly regulations and taxes to lower emissions and move economies away from dependency on fossil fuels. In meeting these challenges there is a risk of backlash to governments, largely from lower-income workers and pensioners who cannot afford to bear the brunt if governments take any measures to control GHGs. Squaring the circle between those who demand fast-track climate-friendly measures and those who want to slow down and mitigate the impact of moving towards a low-carbon future isn't going to be easy, say analysts. In Europe, Central European governments sense the acute political danger to them and have been resisting a European Union plan to join Britain in earmarking 2050 as the year the block has to be net zero" (Dettmer 2019).

6 Indian Perspective

India was influenced by central planning model until the economic reforms of the 1990s. This economic model acted as straggler in its economic growth but was good for environmental perspective with around 1.2 tonnes of CO_2 emissions per head in 1994. This amounted to 3% of global emissions on that date. But after economic liberalization that started in 1990s that resulted in economic growth on one hand but figure of emissions also went up around 3.5 tonnes per person by 2006 and its contribution to total emissions rose 50% as compared to 10 years earlier (Giddens 2009). World Health Organization (WHO) places Delhi as the most polluted city in the world in terms of suspended particulate matter (SPM) (Hindustan Times 2018) as a result of population pressure and haphazard and unplanned Industrial development. Another factor is that emission standards particularly those of motorcycles and scooters numbering around 6,648,730 are a big environmental concern as these vehicles are considered major air polluters due to poor emission standards (Hindustan Times 2018).

(a) **Politics of CNG Fuel**

Environmentalists recommend fuel switching from liquid fuels to natural gas as a strong measure to protect environment. Compressed Natural Gas (CNG) is a lead-free fuel with no sulphur and particulate emissions and 1/10th level of carbon monoxide emissions as compared to petrol. It is thus a highly environment-friendly motor fuel for improving ambient air quality. It also produces much lower carbon dioxide as compared to petrol and diesel oil thereby helping in mitigating global warming (Hilal, 2005). In view of increasing pollution levels in Delhi's atmosphere by diesel-run automobiles, two-wheelers and autorickshaws powered by two-stroke petrol engines, number of directions were issued by the Supreme Court of India from time to time (M.C. Mehta V. Union of India, Writ Petition (C) No. 13029 of 1985). On 28th July 1998, some more directions were issued fixing a time schedule after taking note of the recommendations made by the Bhure Lal Committee. This Committee was constituted on the orders of the Supreme Court under Environmental Protection Act, 1986. The Bhure Lal Committee stressed on the importance of the use of CNG as a fuel and noted that it was imperative to have increased use of CNG as a fuel in Delhi. However, the court in its order on 26th March 2001 observed that neither the government authorities nor private bus operators acted seriously on such directions (Yousuf 2020). The Supreme Court of India made an interesting observation that though CNG at present is available as a clean fuel but entire process of controlling vehicular pollution has been confused whether to opt for CNG as a fuel or not on the pretext of Good CNG or Bad CNG. (M.C. Mehta vs. Union of India, 28 September 2001). All this was under discussion and delay tactics were involved to introduce CNG as fuel in Delhi on safety pretext and other concerns without taking into consideration its useability and efficacy. In Pakistan, the government introduced CNG as fuel in 1992 and large number of buses were running on CNG fuel (Khan and Yasmin 2014).

(b) Coal as Noxious Fuel

Lately, some opportune decisions taken by Government of India shows some seriousness towards issue of climate change. Among G20 nations, India is hailed as a country that has come close to meeting its 2015 Paris Agreement goals. Spending a huge sum of nearly Rs 2,000 crore on its solar energy plan gives an impression that the government seems to be keeping up with its pledge of generating 40 per cent of power from renewable sources (Soni 2020). According to Climate Change Performance Index's (CCPI) report India ranked among the top 10 countries that have adopted substantial measures to curb climate change (CCPI 2021), but there are some forthcoming challenges as well. Although the present government's vision to make India a 5 trillion economy by 2024, environmentalist here has a concern that more than half of the GDP dependents on coal. It being most polluting and responsible for over nine million deaths globally with 50 per cent of such deaths coming from India. Despite this, the central government endures to substantially subsidise the coal mining industry, pumping in nearly Rs 60,000 crore annually. In 2015 the government also introduced the Coal Mines Special Provision Act, which opened the sector to commercial mining by private companies (Paroma, 2020). Public sector Coal India Limited, established in 1975, still contributes 80% of domestic production, of which 80% goes to thermal power plants.

Another challenge to climate change is a recent move by Government of India aiming to create more jobs through the development of existing and new coal blocks in central India. The central government wants India (with the world's fourth-largest coal reserves), to be a net coal exporter (The Economic Times 2020a). Coal Minister is of the opinion that auctioning of 19 coal blocks for commercial mining can generate total revenues of around rupees 7,000 crore per annum and create more than 69,000 jobs once they are operationalized (The Hindu 2020a). This move is not well taken by environmental organizations, even former Environment Minister Jayaram Ramesh has raised his concern on auctioning of coal mines to private sector The Congress leader underlined that what sort of commitment is this towards fighting global warming if coal blocks in very dense forest areas are being opened up for mining. Secondly, the mining and transportation of coal will impose very heavy environmental costs, in terms of loss of dense forests and consequently loss of a valuable carbon sink (The Economic Times 2020b).

The above such initiatives hint us that development has been carried out at the cost of sustainability and may be because India is a developing nation and its first preference is to generate employment opportunities for its people. That is the reason, India's political system is not designed to hold political parties accountable for climate issues, because it is not an electoral priority. Ramachandran Guha, a noted historian of India is of the opinion that it is especially business community and generally middle class who are quite unmindful of the ecological footprints of their lifestyles and issue of urban environmental planning in both internal and external dimension is seriously neglected in media and political circles (Guha 2010). How to address environmental issues in India? Guha suggests that we need to harness scientific and social scientific expertise to develop and promote eco-friendly technologies. Scientific innovations need to be complemented by legislative changes as well as by changes in social behaviour. For this, we need new ideas, new innovations, new institutions and perhaps, a more imaginative and less short-sighted political leadership (Guha 2010).

(c) **Adoption of Electric Vehicles**

Off late in 2013, Government of India started an ambitious National Electric Mobility Mission Plan (NEMMP) 2020 for achieving national fuel security by promoting electric and hybrid vehicles. As part of NEMMP a scheme namely Faster Adoption and Manufacturing of hybrid and electric vehicles in India (FAME) was adopted in the year 2015 with an objective to replace conventional vehicles with hybrid and electric vehicles. In order to boost demand-pull of such vehicles, the government has plans to incentivise buyers by offering monetary support for purchasing such vehicles. Under the scheme, producer of such vehicles will reduce the prices and that will be compensated by the same reimbursement from government side (PIB, NEMMP). In India, top Electric automakers are Mahindra Electric, Tata Motors, Hyundai and Ashok Leyland with Tesla an American company as the new entrant. However, the challenge to electric automakers is that Indian Electric vehicles market is still in a nascent stage. As per Economic Survey of 2019–20 sales of such vehicles till November 2019 was 280,000 units, but most of these vehicles were three-wheelers that run on lead-acid batteries which is again an environmental concern and government has decided to stop offering subsidies to such vehicles unless they switch over to lithium-ion batteries (Hindustan Times, 3 February 2020). The major impediment for adoption of electric mobility in country is high cost of lithium-ison batteries, inadequate charging facilities, electrification of roads and most importantly affordability is impeded by financing procedure of banks and financial institutions who while offering loan look into buyer's paying capacity in case of conventional vehicles but in case of electric vehicles they look into vehicle longevity, battery life, resale value, etc. (Bhat and Agrawal 2021). An independent study of Centre for Energy and Finance (CEEW-CEF) estimates that there is an investment need of 180 billion dollars until 2030 to meet India's electric vehicles ambition programme (The Hindu, 8 December 2020b).

7 Chinese Perspective

Heavy industry was the main focus of socialist economies like former USSR as well of China. In China, however, the initial stage economic growth was propelled by smaller manufacturing plants and the latter stage by heavy industries. Though they brought boom in economy but also resulted in environmental deterioration. State-owned banks of China flushed with capital from overall China's economic success offered their coffers to the state-owned manufacturers. This process began to stagnate in late 2008, as credit around the world became scarce (The Economist 2008).

By this time Pollution from industries has already risen to crucial levels and China realized that the solution to pollution lies in restructuring energy consumption and eliminating production of highly polluting industries. Since 2013, the country took the challenge of pollution seriously and introduced tough anti-pollution measures such as the national action plan on air pollution. The country was divided into provinces for imposing nationwide cap on coal use, for instance Beijing had to reduce coal consumption by 50% between 2013 and 2018. Furthering its efforts, China announced closure or cancellation of 103 coal-fired power plants in March 2017, which were capable of producing more than 50 gigawatts of power (Gardiner 2017). These measures gave hopeful sign of flattening the curve of CO_2 emissions, However, CO_2 emissions from China continued to rise until 2019 even as much of the world began to shift away from fossil fuels (McGrath 2020). Latest Climate Change Performance Index of 2020 places China at 33rd rank (CCPI 2021) and it appears that China has rolled back its policies of restriction on coal plants. In 2020 more coal plants were allowed than in 2018 and 2019 combined. China now possesses roughly half of the world's coal power capacity and coal-fired power plants, which indicates going against the global commitments (Climate action tracker).

Surprisingly, very recently in September 2020 President Xi Jinping made a bold statement that China will strengthen its 2030 climate target (NDC), peak emissions before 2030 and aim to achieve carbon neutrality before 2060. "By playing the climate card a little differently, Xi has not only injected much needed momentum to global climate politics, but presented an intriguing geopolitical question in front of the world: on a global common issue, China has moved ahead regardless of the US. Will Washington follow?" (McGrath 2020).

8 European Perspective

The EU is at the forefront in setting out a trend by committing itself to significant cuts in greenhouse gas emissions to limit global warming. European Union as community of nations gives a hope when it comes to initiatives in controlling greenhouse gas emissions, be it Kyoto Protocol or latest Paris Climate Agreement. Climate finance which is a long-term demand of developing countries is getting their lead support from the European Union in tackling climate change (European Commission). Under Kyoto Protocol different targets were negotiated for cutting of greenhouse gas emissions, like USA was supposed to cut it by 7% and for European Union (EU) it was 8%. This was to be attained by multiple steps like emission trading for which EU setup its own system in 2005 and by Joint Implementation and the Clean Development Mechanism (CDM). By 2012, the only major signatory committed to the Protocol and its extension was EU (Baylis et al. 2017).

EU not only played an instrumental role for the Paris Climate Agreement (2015) but also formally ratified the agreement in 2016. European Union feels privileged in achieving its 2020 emission target reduction as in 2018, its GHG emissions were lower than in 1990 (European Commission). Forwarding its commitments for reducing emissions it established net zero goal along with scenario for how to achieve it. Its focus is now on revising integrating national energy and climate plans for target of 2030 climate and energy framework (Bazilian and Gielen 2020). Under its 2030 target, EU's nationally determined contribution (NDC) is to reduce emissions by 40% as compared to 1990 and for achieving this all key EU legislation was adopted by closing 2018 (European Commission). For net zero emission targets of 2050, the European Commission is working under "Green Deal" initiative published in 2019. This initiative was endorsed by leaders of European Council in December 2019, however, Poland refused to commit to its implementation. The objection of Poland stems from fulfilling its energy needs which are directly dependent on coal. Economic activities of many towns of Poland and more than a quarter-million Polish jobs are related to the fossil fuel industry. "You can't expect Poland to leap to zero carbon in 30 years," stated by Marchin Nowak, a coal industry executive (Dettmer 2019). Green Deal is a package of measures for cutting GHGs through investment in cutting-edge research and innovation. Under the Deal, EU wants to have a European Climate Law by incorporating 2050 climate-neutrality goals in it. Another ambitious goal of the Deal is European Climate Pact with the aim of engaging citizens and all parts of society in climate action. In 2018 Climate Action Network Europe has published a report titled "Off target Ranking of EU countries" to assess the progress European Member States have achieved in fighting climate change under Paris Agreement like progress in reduction of carbon emissions and promotion of renewable energy and energy efficiency at home. In its ranking all EU countries were placed on off-target place. The report illustrates that Belgium, Denmark, Germany and the UK are no longer at the forefront of the fight against climate change and aim rather low despite their relative wealth (Off target Ranking of EU countries, June 2018).

9 The Climate Change Performance Index 2021

The Climate Change Performance Index is developed by collective efforts of non-profit organizations German Watch, New Climate Institute (Germany) and Climate Action Network (CAN International). The objective of this Index is to assess the progress made by 57 countries and the European Union, who are collectively responsible for 90% global greenhouse gas emissions in the four categories namely GHG emissions (40%), Renewable energy (20%), Energy use (20%) and Climate Policy (20%). The Index prepared so enhances transparency in climate politics at international level and enables comparison of climate protection measures and progress made by individual countries.

Top 10 nations on the Climate Change Performance Index 2021

Climate Change Performance Index 2021		
Rank	**Country**	**Score**
1	(None achieved 1-3 rank)	
2		
3		
4	Sweden	74.42
5	United Kingdom	69.66
6	Denmark	69.42
7	Morocco	67.59
8	Norway	64.45
9	Chile	64.05
10	India	63.98

Source www.ccip.org

CCPI-2021 places European Union (EU) climate action in two different shades. One for Scandinavian EU countries, Portugal and the EU ranking high on the index with relatively good indicators, and the other within the block as laggards like Hungary, Poland and the Czech Republic. In overall performance, EU has been placed at 16th place which is a quantum jump from its previous year's 22nd place. The report mentions that it is because of better climate policy of EU that has improved its climate performance index. The EU has the capability to become a role model for other countries by setting desirous climate target for 2030 in line with the 1.5 °C limit and further development of its Green Deal. The report also cautions that it can stumble badly if it pursues greenwashing instead of green recovery and implements inadequate targets and instruments in the European Green Deal (CCPI 2021).

10 Conclusion

Development of a sense of belongingness to this planet as our common home starting from self, home, society and nation-state to reduce the use of all those utilities which are causing global warming is the need of the hour. Inculcating climate friendly values in present and coming generations will produce a voice that will be heard and respected in future. Governments will be held accountable by voting and electing those who work for climate friendly initiatives. The scientific community with political support must develop new low-emissions technologies that may answer supply push factors like targeted low-cost credit accessibility and demand-pull factors. Special attention and cooperation should be paid to those countries who excel in Climate Performance Index by UN and Intergovernmental Organizations, which will be a motivation for other countries to perform for the cause. Climate finance, capacity building and technology transfer is another area which needs attention of national governments and world community. These initiatives shall not remain limited to seminars, conferences and global summits but should be legally binding actions at the local, national and global levels.

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Technological Solutions to Mitigating Climate Change

Richard Betts

Abstract This chapter will consider solutions to mitigating climate change. Focus will consider primarily technological solutions, but consideration will also be given to nature-based solutions such as conservation of forests and restoration through rewilding and afforestation. The natural world is our greatest ally in tackling the climate crisis and our green assets such as our forests, swamps and oceans are currently absorbing most of our carbon pollution. We need to protect our remaining green assets and support their restoration at scale so that we can mitigate the worst of global warming and start to reverse it. In short, technological solutions to the climate crisis, and to the connected biodiversity crisis, are of course essential but they need to supplement nature-based solutions and cannot replace them.

Keywords Climate crises · Climate resilience · Mitigation · Decarbonization pathways · Clean energy · Electric vehicles

1 Introduction

This chapter will consider solutions to mitigating climate change. Focus will consider primarily technological solutions, but consideration will also be given to nature-based solutions such as conservation of forests and restoration through rewilding and afforestation. The natural world is our greatest ally in tackling the climate crisis and our green assets such as our forests, swamps and oceans are currently absorbing most of our carbon pollution. We need to protect our remaining green assets and support their restoration at scale so that we can mitigate the worst of global warming and start to reverse it. In short, technological solutions to the climate crisis, and to the connected biodiversity crisis, are of course essential but they need to supplement nature-based solutions and cannot replace them.

Firstly, as high-level context, the Paris Agreement, the first global agreement on climate change, has been ratified by all but 7 countries globally as of early 2021. Donald Trump took the US out of the Paris Agreement in November 2020, but new

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US President, Joe Biden, reinstated the US as soon as he assumed the Presidency in January 2021. The Paris Agreement aims, through rapid decarbonization, to limit the increase in global average temperature to well below 2 °C[1] above pre-industrial levels; and to pursue efforts to limit the increase to a maximum of 1.5 °C, recognizing that this would substantially reduce the risks and impacts of climate change. It also aims to increase the ability of countries to adapt to the adverse impacts of climate change and make ‘finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development’. The Paris Agreement temperature goals should be considered absolute maximum increases. Following the IPCC Special Report, published in 2016, a 2 °C increase is now considered too dangerous as there is too high a risk that it would push the earth’s climate system past a ‘tipping point’ that due to planetary feedback loops would lead to runaway warming and to a global hothouse earth by the end of the current century. However, just in the last few years, there have been extreme climate-related events, unprecedented in severity and frequency, from Australia to California and from the Amazon to the Arctic amongst many others. Hence, global warming since pre-industrial levels, currently around 1–1.1 °C and increasing, is already causing climate-related disasters, economic and human costs across the world. Hence, the goal really needs to be to strive to reduce any warming to a minimum and for this future warming that is currently already built into the earth’s system due to feedback loops, to be reversed as soon as possible.

In addition to the Paris international accord, recently, and notwithstanding the enormous disruption of the global C-19 crisis, many national and local governments and companies, amongst other actors, have stepped forward to increase their climate ambition and commit to net zero climate pledges. At the time of writing in early 2021, for example, net zero commitments at or earlier than around mid-century have been announced by China, Japan, South Korea, the EU, UK, Canada and South Africa along with many smaller national states. The new US President, Joe Biden, has also pledged to bring into force a net zero plan for the US now that he has formally taking office. It is likely that this momentum will create further encouragement for other countries to follow suit. As encouraging as these initiatives all are, we must recognize that making a commitment is only the first step. Even more critical is the need for rapid implementation and enforcement. This chapter will consider key solutions that can enable this.

2 Jevons Paradox and Rebound Effects

Since the start of the Industrial Revolution, new energy sources have emerged that have slowed, but not stopped, the growth of other energy sources. For example, coal was replaced by oil in many forms of transportation, but global coal consumption

[1] All global warming data is reported based on global averages. Some parts of the World are warming at a much faster rate than the global average. In general, land areas are warming at around twice the rate of the oceans and the Poles are the areas of the World experiencing the most rapid warming.

has also continued to increase. Globally energy usage has risen at the same time as those efficiencies and can even be enabled by them. This is known as Jevons Paradox after the English economist William Stanley Jevon who observed in 1865 how technological improvements that increased the efficiency of coal-use actually led to the increased consumption of coal in a wide range of industries. Similar trends have been observed in other areas such as with the use of oil and natural gas. In sum, energy efficiency can often lead to an increase in total demand, rather than a decrease. In addition to Jevons Paradox, other important rebound effects have been identified. Rebound effects occur when some of the savings from energy efficiency are cancelled out by changes in people's behavior. For example, savings from the use of more energy-efficient products in the household would be more than offset if they were used to purchase long-haul flight tickets.

The crucial insight these examples provide is that when considering pathways for decarbonization, we need to take a systems approach that considers our highly interconnected global economy and planetary systems together rather than considering issues or solutions in isolation. Hence, energy efficiency measures in isolation may not help and may even be counter-productive if they lead to increased energy consumption overall. Rapid growth in renewable energy will not be enough if fossil fuel consumption also increases. What we need is to rapidly increase the supply of renewable energy whilst maintaining, or decreasing, the total level of energy consumption so that fossil fuel use is also reduced. This will also then negate rebound effects.

3 Embodied Carbon

In considering all the potential technological solutions, it is essential that the total life cycle environmental impact, and not just the operational impact, is considered. Embodied impact includes the energy and CO_2e emissions released to create, manufacture, transport, use and dispose of each technology. Though essential, the information on the whole life CO_2e impact of each technology tends to be very limited. To assess embodied impact, a Life Cycle Assessment (LCA) is required, of which there are different types each with different attributes and challenges as explored in a paper by (Finnegan et al. 2018). Key to the development of the LCA is the creation of a Life Cycle Inventory (LCI) and at present there are 3 approaches, each with its pros and cons, to creating this inventory: (i) process analysis (ii) input–output analysis (IOA) and (iii) hybrid analysis (Crawford et al. 2017). Each can be used to calculate the total energy use and whole life cycle CO_2e impact.

Nevertheless, it should be emphasized that although there is a significant embodied CO_2e footprint for some clean technologies, the savings made during the use stage tend to greatly overshadow these results (Finnegan et al. 2018). For example, studies indicate that solar panels need, on average, up to 4 years to produce enough energy to compensate for the energy used in their energy-intensive production phases (NREL).

4 1.5 °C Decarbonization Pathways (IPCC 2016)

Moving to consider pathways for decarbonization, the IPCC's influential Special Report presents a range of potential 1.5 °C decarbonization pathways. Clearly, all are scenarios and since being published in 2016, the costs of many clean technologies such as solar and wind have reduced dramatically. The plummeting costs and further breakthroughs in new technology mean that the potential mix of solutions for decarbonization also needs to be continually reassessed. This includes, for example, the extent to which fossil fuel solutions such as natural gas, and also nuclear technology, will be needed as bridging solutions in light of the rapid improvements of many renewable technologies and plummeting costs. Furthermore, in many areas technological change is extremely rapid and hence to try and model decarbonization pathways through to 2050 and beyond is fraught with many uncertainties due to the rapidly changing landscape. As a result, discussion here will be limited to an overview of what is needed before delving into more detail for many of the solutions.

Figure 1 shows a range of decarbonization scenarios for global primary energy supply and electricity generation as examples. As can be seen in Fig. 1a, all scenarios

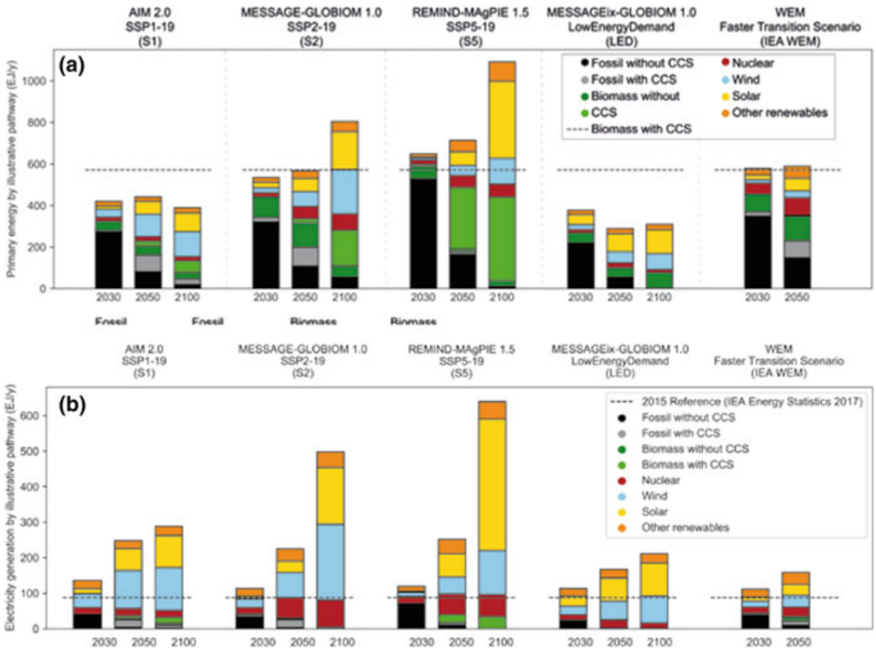

Fig. 1 1.5 °C decarbonization pathways for primary energy supply under different scenarios **a** and for the electricity sector **b**[2]

[2] *Source* IPCC Special Report (2016) Figs. 2.15 and 2.16.

show rapid decrease in fossil fuels without CCS after 2030 and after 2050 nearly all fossil consumption is with CCS. Solar and wind dominate the energy mix along with fossil use with CCS essentially in all decarbonization pathways. Nuclear, though much smaller, is modelled to increase substantially from current levels in most decarbonization pathways.

As Fig. 1b shows, there is a clearer decarbonization pathway for the electricity sector. All the scenarios show rapid uptake of renewable energy, which is seen as coming mainly from solar and wind. Nuclear is seen as being needed in all scenarios and as being an important contributor (up to 20%) in 2 of the 5 example scenarios. By 2050 electricity generation from fossil fuels is shown as zero or only minor in all scenarios and nearly all of this is with Carbon Capture and Storage (CCS).

5 Renewables Introduction

Due to technology improvements and greatly reduced costs globally, renewables such as solar and wind are now competitive with fossil fuels in most places of the world. Indeed, a recent article in Bloomberg Green reported how for at least two-thirds of the global population solar and wind were already cheaper than fossil fuels and how just 10 years ago, solar exceeded $300 a megawatt-hour and onshore wind was more than $100 per megawatt-hour, whilst in 2020 onshore wind is currently around $37 in the U.S. and $30 in Brazil, whilst solar is $38 in China (Quinson, 2020). It should also be borne in mind that this analysis is based on direct costs only and excludes the cost of negative externalities such as carbon emissions and air pollution from fossil fuels.

In addition to technological improvements and reduced costs, the fossil fuel divestment movement, which started around 10 years ago as a grassroots movement in the US, has now become globally significant. The situation is changing rapidly but as of January 2021, over 1,200 institutions had begun or committed to a divestment from fossil fuels totaling over $14.5 trillion. Consequently, there is also increased focus on the risk of stranded assets from fossil fuels. According to recent studies, for the world to stay within a 1.5 °C carbon budget, most of the world's fossil fuels need to be left in the ground, or potentially only used with CCS. Partly as a result of these trends and the associated uncertainty over future oil prices, in 2020, both BP and Shell (2020) wrote down the value of their exploratory assets by billions of dollars. 2020 also witnessed a spate of shale gas bankruptcies in the US whilst Exxon was removed from the DJ index after a century. In 2020, Exxon, previously the most valuable company in the world, was briefly surpassed by NextEra, America's largest renewable energy company, as that country's most valuable energy company in another major milestone for renewables (Egan et al., 2020).

In short, renewables such as solar and wind are now disrupting traditional industries including the power sector. They are also disruptive industries since they can eliminate the concept of businesses and individuals as just customers by transforming them into prosumers (producer–consumers) that compete with the electricity utilities at the same time they buy from them. Indeed, as an example, European energy utilities have lost an estimated half a trillion euros in asset value over the last decade (Economist, 2013), partly because the emerging renewable energy market is highly decentralized with many new competitors as individuals and businesses can all be their own power plants.

6 Solar Energy

Moving on to consider the main renewable technologies, starting with solar energy, aside from a small share of global energy provided by nuclear energy, currently around 10% (World Nuclear Association, 2020), and a tiny portion of tidal power (which essentially originates from the moon), nearly all our energy supply originates from the sun.

At any given time, there is currently a massive 16,300 kW of solar energy arriving on the Earth's surface for every person in the world (Berners, 2019). Though some parts of the world are blessed with more abundant solar energy, the overall abundance of the sun's energy means that most places should have enough for now. Indeed, an IEA report indicated that the world's current primary energy demand could be met potentially by covering up to just 8% of the world's major deserts with solar panels (IEA, 2015) provided that the energy could be stored and transmitted over long distances. Indeed, long-distance transmission is essential since the areas of highest potential for solar energy often include areas such as deserts that are often located far from population centres. Long-distance transmission is becoming more feasible due to major improvements in cabling technologies including the use of high voltage direct current (HVDC) cables that can replace high voltage ACs used at present. Though the initial loss of electricity from transmission is greater with HVDC, losses do not increase with distance, as opposed to ACs, which means they can source electricity from a much larger area. HVDC cabling technologies offer the potential of major economies of scale since they enable large-scale solar and wind parks, often far from civilization, to be connected to major population centres. They can also help overcome problems of intermittency: when there is not a strong wind, solar is likely to still be possible, at least during the day. At night-time, if solar power is not possible, wind power may be.

Solar energy currently provides around 2% of global energy mainly through solar photovoltaic (PV) panels. Most photovoltaic panels currently on the market tend to capture around 15–22% of the sun's energy (Zeledon, 2018) whilst latest studies have achieved efficiencies of around 40% but these panels are not publicly available (Empire Renewable Energy).

Though solar panels can provide zero-carbon energy for many years, it is essential to consider the full life cycle impacts for all technologies. In terms of solar, solar panel production relies on energy-intensive processes during the mining of the quartz sand and subsequent refining into silicon (Mulvaney, 2014). What this means is that on average solar panels need at present 1–4 years to produce enough energy to compensate for the energy used in their earlier production phases according to NREL. Solar panels, and also wind turbines, should be designed to optimize life cycle performance and also with circularity principles in mind. For example, applying circularity principles means solar panels should be designed in a way that the constituent parts can be easily disassembled at the end of their useful life as this will allow components to be reused in new products and applications, minimizing landfill and reducing the amount of new materials needed in the energy-intensive phases at the start of the life cycle for solar panels and also wind turbines.

7 Concentrating Solar Thermal Power (CSP)

CSP systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight onto a receiver. Whilst solar PV has been growing rapidly in recent years, solar CSP growth has been slow due to technical difficulties and high prices. In 2017, CSP represented less than 2% of worldwide installed capacity of solar electricity plants (Lilliestam, 2017). However, CSP is considered to have significant potential not least as it can be used for storing energy during the night and hence in helping to balance renewable energy production. As of 2019, global CSP capacity was 6.2 GW, with 600 MW of capacity coming online during that year (REN, 2020).

8 Space-Based Solar Power (SBSP)

Space-based solar power (SBSP) is the concept of collecting solar power in outer space and distributing it to Earth. One key benefit would be the potential to secure a permanent source of clean energy, not susceptible to the diurnal cycles on Earth. Another would be to secure much more powerful energy since a large fraction of incoming solar energy (55–60%) is lost on its way through the Earth's atmosphere by the effects of reflection and absorption.

At present, SBSP is a technology that could offer great potential but probably not until the second half of this century. SBSP is currently under investigation by countries including China, Japan, Russia, the United Kingdom and the US and China announced in 2019 that it had launched a project to develop a first solar station in space (Snowden, 2019). Though at present it seems like it will be a technology for the relatively distant future; not least because the costs would currently be prohibitively expensive to start with, the hope is that it will be possible to leverage new technologies to greatly reduce the costs and the energy consumption in the initial phases. For example, it might become possible to use new technologies such as 3D printing so that solar stations could be assembled in space; as this would make it cheaper and much less energy-intensive to install them there. Similarly, if in the distant future humans can establish an off-world industrial base it could become possible to manufacture solar power satellites out of asteroids or lunar material.

In addition to the costs and feasibility of the technology, there would be other important obstacles to address including health concerns linked to solar radiation and the inaccessibility and hostility of the space environment meaning that installation and maintenance would probably need to be done telerobotically.

9 Wind

Wind energy is the use of wind to power wind turbines to turn electric generators for electrical power. It is a renewable source of power with much smaller life cycle greenhouse gas emissions than fossil fuel combustion (Table 1). In recent years, wind energy has been growing rapidly. In the last few years, wind energy costs for both onshore and offshore wind have reduced dramatically due to economies of scale and improvements in technology. With no fuel costs and maintenance costs that have been greatly reduced due to recent technological improvements such as gearless wind turbines that have far fewer moving parts, wind is becoming extremely competitive in the energy sector. The cost of financing is also becoming cheaper due to its lower risk profile as the technology has started maturing.

Nevertheless, it has been estimated that from the solar energy that lands on earth only around 2% is converted into wind energy (Smill, 2017). Furthermore, most of that 2% is inaccessible to humans as it is high up in the jet stream whilst most of the low altitude wind is far out at sea. There are also many constraints in terms of geography and other land uses that restrict the remaining amount of wind that can be accessed from land and coastal areas. Hence, though wind power can clearly be important in contributing to decarbonization and significant in some regions such as the British Isles, which are surrounded by windy seas, at a global level it seems unlikely to be able to contribute anywhere near as much renewable energy as solar energy.

Table 1 Life cycle CO_2-equivalent (including albedo effect) from selected electricity supply technologies (gCO_2eq/kWh) IPCC (2018)

Technology	Min.	Median	Max.
Pulverized coal	740	820	910
Gas-combined cycle	410	490	650
Hydropower	1	24	2,200
Solar PV–utility scale	18	48	180
Wind offshore	8	12	35
Nuclear	3.7	12	110

10 Offshore Wind

The last few years have witnessed major breakthroughs in terms of offshore wind. Many of the largest developments are currently around the British Isles. For example, Walney Extension in the Irish Sea, which is currently the largest offshore wind farm in the world, can supply over one million homes with renewable energy. However, still larger offshore wind parks are being installed off the English coast in the North Sea. Hornsea 1, 2 and 3 are all set to supply more than 1 million homes once they become fully operational over the next few years.

These major wind parks have been designed close to the coasts of England in order to be able to supply some of the heavily populated areas in the North of England. However, the UK has far more practicable resources, windier seas, off its other coasts but these have been less accessible and are further from the main population centres. Nevertheless, rapid recent improvements in technology have driven the supply chain costs down, allowing larger blades to be constructed and in deeper waters. As an example of a recent technological breakthrough, the world's first floating station has recently been built in Scotland. Floating stations offer the potential to expand offshore wind to areas where winds are strongest and most consistent (rather than where ocean topography is smoothest for turbines), creating the possibility of sourcing wind energy from many areas that have hitherto been inaccessible. As the technology improves still further, more areas will become accessible.

Offshore wind can also have advantages over onshore wind such as fewer planning restrictions or competing pressures for other land uses and no objections from NIMBYs[3] or NIMTOs.[4] Nevertheless, in some regions, onshore wind is already providing a substantial amount of local electricity needs as discussed in the next sub-section.

11 Onshore Wind

Many of the largest operational onshore wind farms are in China, India, and the United States. As of early 2021, the largest onshore wind park in the world is the Gansu park in China, which when fully constructed will have a capacity of 20 GW. Unfortunately, due to weak demand, to date around 60% of the wind park's capacity has gone unused (Vyas, 2018).

In addition to their environmental benefits such as zero emissions during operation, onshore wind turbines also provide farmers and other landowners with an opportunity to diversify their income and increase land value through the lease payments due from the wind energy company. Nevertheless, many people are currently critical of

[3] NIMBY–acronym meaning 'not in my backyard', which is used to describe opposition by residents to proposed developments in their local area.

[4] NIMTO–acronym meaning 'not in my term of office', which is used to describe political leaders not wanting to implement a change during their mandate.

onshore wind farms, in part for the reasons noted in the preceding section, and also over concerns of their visual impact on the landscape.

12 Off-Grid Solutions

Despite rapid improvements in renewable electricity and plummeting prices, in 2018 almost 800 million people still did not have access to electricity (WHO, 2020). For example, in Africa, solar, wind and hydroelectric power are all growing rapidly but with a rapidly increasing population currently set to reach 4 billion by 2100, it is essential to staying within the world's carbon budget that Africa adopts a renewable pathway and that globally renewable electricity can be rolled out rapidly in emerging economies. Hence, off-grid technologies, also known as distribution renewables for energy access (DREA) technologies, which are renewable energy supply technologies operating independent of the national grid will be essential in many emerging economies.

13 Hydropower

Hydropower refers to power that is derived from the energy of falling or fast-running water, which may be harnessed for useful purposes. The most common use is for generating electricity, in which case it is known as hydroelectric power. Hydropower is produced in 150 countries. China is the largest producer and other countries where hydropower provides a significant share of primary power include countries with a lot of forest cover such as many of the Amazon countries in South America, Canada and Sweden. The cost of hydroelectricity is relatively low, making it a competitive source of renewable electricity.

A dam and reservoir are used to enable a flexible source of electricity, since the amount produced by the station can be increased up or down very rapidly to adapt to changing energy demands. In 2015, hydropower generated 17% of the world's total electricity and 70% of all renewable electricity (REN, 2020). However, global growth in hydropower has slowed in recent years, perhaps at least in part because the technology is arguably starting to approach what is possible in terms of geography. For example, in his book '*There is no Planet B*', Berners Lee calculated the maximum potential for hydroelectricity production. The calculation was based on first determining the amount of rain at different altitudes as a guide for the theoretical maximum potential energy in global rainfall. From this, he contended that potentially up to 5% of the potential head of water could be put through turbines and that even if those turbines were 80% efficient, today's global hydroelectricity production, at 0.45 TW, would already be at least two-thirds of the way to its maximum potential (Berners Lee, 2019).

Once constructed, a HEP station produces no direct waste, and it can have a considerably lower output level of life cycle greenhouse gases than not just fossil fuel-powered energy plants but also renewable plants such as solar PV. However, hydroelectric power is also subject to significant criticism due to the major alterations that can arise in the local catchment biodiversity due to dam construction. Furthermore, when constructed in lowland rainforest areas, since part of the forest needs to be inundated, HEPs can be responsible for large amounts of methane (a powerful greenhouse gas) and consequently much higher greenhouse gas emissions even than a coal-fired power station.

14 Bio-Power Technologies

Bio-power technologies convert renewable biomass fuels into heat and electricity using similar processes to those used with fossil fuels. Biomass refers to any plant or animal matter reused as a source of heat or electricity, such as sugarcane, vegetable oils, wood, organic waste and agricultural residues. Ways to release the energy stored in biomass to produce bio-power include direct combustion, bacterial decay and conversion to gas or liquid fuel (https://www.energy.gov/eere/bioenergy/biopower-basics). Most of IPCC's GHG mitigation pathways include substantial deployment of bioenergy technologies. Some researchers dispute the claim that the use of forest biomass for energy is carbon neutral. However, it is currently the mainstream view, supported by, *inter alia*, the IPCC, FAO and IEA.

Most electricity generated from biomass is produced by direct combustion. Biomass is burned in a boiler to produce high-pressure steam, which flows over a series of turbine blades, causing them to rotate. This rotation drives a generator, which produces electricity. In combined heat and power (CHP) facilities, the steam from the power plant can be used for manufacturing processes or to heat buildings. For example, wood waste is often used to produce both electricity and steam at paper mills.

In terms of bacterial decay, organic waste material, such as animal dung or human sewage, is collected in oxygen-free tanks where the material is decomposed by anaerobic bacteria that produce methane and other byproducts to form a renewable natural gas, which can then be purified and used to generate electricity.

Biomass can also be converted to a gaseous or liquid fuel through gasification and pyrolysis.

As explored elsewhere in this chapter, when considering using biomass as a feedstock, it is critical to take a holistic approach and mitigate other potentially significant negative externalities that may arise, such as exacerbating deforestation or food hunger risks if more land is allocated to biofuel crops. Where bio-power can be used sustainably, the consensus is that in the short term, emissions from bio-power might rise compared to a no-bioenergy scenario. This is because, as explained by the IPCC, forest carbon emission avoidance strategies give a short-term carbon benefit but these may be overcompensated over the longer-term if, for example, biomass is sourced sustainably from forests (IPCC, 2019).

15 Geothermal Energy

Geothermal energy is thermal energy generated and stored in the Earth, which originated from the original formation of the planet and from radioactive decay of materials. Geothermal power is considered cost-effective, reliable, sustainable, and environmentally friendly (Glassley, 2015), but has historically been limited to areas near tectonic plate boundaries. Recent technological advances have dramatically expanded the range and size of viable resources, especially for applications such as home heating by using geothermal or ground source heat pumps (GSHP), opening a potential for widespread exploitation. Geothermal wells release greenhouse gases trapped deep within the Earth, but these emissions are much lower per energy unit than those of fossil fuel.

Geothermal power is considered renewable because any projected heat extraction is small compared to the Earth's heat content. The Earth has an internal heat content that is approximately 100 billion times the 2010 worldwide annual energy consumption (Fridleifsson et al., 2010). The planet is slowly cooling down on geologic timescales and human extraction currently taps a minute fraction of the natural outflow. However, although theoretically Earth's geothermal resources could more than sufficiently supply the world's energy needs, only a very small fraction can be profitably exploited as drilling and exploration for deep resources is very expensive.

Globally, the countries with the most installed geothermal electric capacity are currently the US, Philippines, Indonesia, Mexico and Italy. At the end of 2019, the IGA (International Geothermal Association) reported that total global installed capacity was around 15.4 GW but that globally, geothermal power generation capacity could almost double to around 28 GW in the next 15–20 years (IGA, 2020).

16 Air Source Heat Pump (ASHP)

Another form of heat pump that can be used to replace a conventional heating system is an Air Source Heat Pump (ASHP). In short, the pump absorbs heat from the outside air to supplement underfloor heating systems and/or provide hot water. The ASHP can extract heat from the outside air even when temperatures are as low as − 15 °C (Finnegan et al., 2018).

In sum, heat pumps are increasingly seen as an essential solution for heat decarbonization. Though the technologies already exist they are not yet widely in use. However, momentum is now starting to accelerate. For example, the UK Government's recent 10-point plan for a green industrial revolution, brought forward the ban on gas boilers for new homes to 2023 and introduced a new target to install 600,000 heat pumps every year by 2028 (ISO Energy). The UK Government's official advisors, the Committee on Climate Change (CCC), report that 19 million heat pumps need to be installed in the UK by 2050 Net Zero (2019).

17 Wave and Tidal Energy

Some studies have suggested that wave and tidal energy could supply at least 10% of the world's energy consumption (SEED). Nevertheless, most deployments to date have been small-scale demonstration and pilot projects and these resources remain largely untapped. However, due to recent advances in research and technology they are now starting to become more competitive. At the end of 2019, there was an estimated 535 MW of operating capacity concentrated mainly in Europe (REN, 2020).

18 Tidal Energy

Tides are more predictable than the wind and the sun. Tidal power is taken from the Earth's oceanic tides, which captures the energy of the current caused by the gravitational pull of the Sun and Moon. The world's largest tidal power station in terms of output is currently the Sihwa Lake Tidal Power Station in South Korea, which opened in August 2011 Tidal Power Station.

19 Wave Power

Wave power is the capture of energy of wind waves for purposes such as electricity generation. Global resources of coastal wave energy have been estimated as being in excess of 2 TW[40]. Locations with the greatest potential for wave power include western Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand. In 2000 the world's first commercial Wave Power Device, the Islay LIMPET, was installed on the coast in Scotland and connected to the National Grid (Edie, 2000) before being subsequently decommissioned in 2012 (BBC, 2013).

20 Nuclear

Nuclear power plants can generate electricity without emitting carbon pollution and that can seem cheap when calculated on the cost of electricity per kilowatt, but only if governments assume responsibility for insurance risks and responsibility for waste disposal. Nuclear energy is also a stable energy source, which means it can provide a more stable energy supply than renewables can at present. Hence, even if more expensive than renewables, there can be justification for using some nuclear in the energy mix as a baseload. However, given how rapidly solar and wind power can become operational, coupled with their plummeting costs, there can also be an opportunity cost with nuclear: in the decade or so it may take to get a new nuclear plant up and running, in many cases other low carbon technologies could have been used and for a much smaller investment.

Undoubtedly of all the energy types, none divides opinion as strongly as nuclear power does having both strong supporters and critics. Since the 1950s there have been a handful of major high-profile nuclear disasters including at Fukushima, Japan (2011), Chernobyl, in the current Ukraine (1986) and the Three Mile Island accident in the US (1979). Nevertheless, supporters could also cite a NASA study that indicates when the whole life cycle is considered nuclear deaths have been much lower than many alternatives and that the use of nuclear energy helped avoid 1.84 million premature air pollution-related deaths over the period 1971–2009 (Kharecha et al., 2013).

Advocates of nuclear also argue that nuclear energy has enabled the world to avoid billions of tonnes of greenhouse gas emissions and during a period when often there were no other viable low carbon alternatives. Indeed, estimates of the savings from high-profile studies have been in the range of 55–64 billion tonnes since the mid-1970s (IEA; Biello (2013).

According to statistics from the IEA the number of nuclear power plants increased rapidly from the industry's beginning in the 1950s with global nuclear power-generating capacity peaking in 2010 at 375 GWs. Since then, however, nuclear's share of the global energy mix has been in decline (Gourmellon, 2014). In 1996, nuclear power supplied around 18% of the world's electricity (OECD, 2011) but by 2020 this had declined to around just 10% (World Nuclear Association, 2020). As contrast, renewables (including hydroelectric power) contributed 19% of global electricity generation capacity in 2000 but 26% by 2019 (Ritchie et al., 2015).

Nuclear power is well established in some countries such as China but nuclear has lost support in other countries recently where it had been widely used. For example, in the aftermath of the accident at the Fukushima I Nuclear Power Plant in 2011 in Japan, the public backlash against nuclear energy that ensued resulted in all the country's nuclear plants being shut down by the following year. Similarly, following the disaster, plans for nuclear plants were abandoned in countries around the world including Malaysia, the Philippines and Taiwan (Flannery, 2015). However, the biggest reaction was arguably in Germany where at the time of the disaster nuclear power plants provided around 17% of the country's power but where the German government announced it would shut all the country's nuclear plants by 2022 just shortly after the disaster (World Nuclear Association, 2015). Even France, which has been a world leader in nuclear technology, has announced plans to reduce its dependence on nuclear power from 75–50% by 2025 with the reduction being replaced by massive investments in solar and wind power (Carnegy, 2014).

In addition to concerns over safety, the financial considerations have changed significantly recently. As already noted, the cost of solar and wind has plummeted whilst nuclear has become more expensive, for example due to increased safety and security costs. Solar and wind assets can be acquired seemingly ever more cheaply at small scale and can become operational in a very short space of time. Conversely, nuclear power is only viable for large-scale investments that cost billions of dollars and typically take years to complete with the financial investment taking decades to pay off. Given that solar and wind power are still less mature technologies, at an earlier stage of the 'learning' curve, their cost can be expected to continue to decrease and the price differential with nuclear continue to increase. Hence, new nuclear power is currently increasingly looking viable only where governments are prepared to intervene and provide large-scale financial support such as subsidies as well as to accept insurance risk and decommissioning responsibilities.

Moreover, the issue of long-term storage of high-level nuclear waste remains highly problematic. Despite the fact the waste will remain highly radioactive for thousands of years, there is not currently a single long-term, high-level nuclear waste facility anywhere in the world (World Nuclear Association, 2015). Concerns over radioactive waste and storage concern both routine and accidental radioactive discharges into the environment. Critics also worry about the risk of nuclear proliferation, since the basic process used for nuclear energy is essentially the same as that used for nuclear weapons.

Notwithstanding the limitations, supporters could argue that at least the toxic waste is stored—unlike some of the waste from O&G such as carbon emissions, which are currently released at all stages of the O&G life cycle and are major contributors to the global climate crisis.

Currently, there are more nuclear power stations reaching retirement age than there are new ones in the pipeline and building a new one is a much bigger investment than, as a contrast, putting up a few million solar panels. Hence, in sum, it seems unlikely there will be a major uptake of nuclear energy other than perhaps at the local level in a few countries where there is favourable Government support. Nuclear energy is a sizable component of the energy mix in numerous countries and nuclear reactors can be in use for decades. Hence, due to the plummeting prices of renewables and increased safety concerns, it is unlikely that the contribution of nuclear to the global energy mix will substantially increase and is more likely to decrease. Having said that, despite the cost, nuclear energy does provide a more stable baseload than renewable solutions currently do, though this can be expected to change in the coming years with continued improvements to storage technologies and also to green hydrogen. In addition, recent breakthroughs in nuclear technology using a thorium reactor offer the potential for safer, cleaner and much more abundant energy and much less nuclear waste production (Martin, 2019). As an example of the abundance of thorium, The Thorium Energy Alliance estimates that just in the US there is enough thorium to power the country at its current energy level for over 1,000 years (World Nuclear Association, 2020). Furthermore, according to studies, just 1 tonne of thorium provides the same energy as 200 tonnes of uranium or 3.5 million tonnes of coal The Green Age (2020). However, development of thorium power is in its infancy and hence initially start-up costs would likely be extremely high and as of early 2021, there are no operational thorium reactors in the world (Forsberg et al., 1999). Nevertheless, thorium technology has the potential to be both a game changer for nuclear energy and being able to contribute significantly to global decarbonization goals.

21 Nuclear Fusion

Fusion is the process that powers the Sun and other stars, where hydrogen atoms fuse together to form helium, and matter is converted into energy. According to recent studies, a viable nuclear fusion reactor could be developed by 2025 (Choi, 2020; Creely, 2020). If such a breakthrough for nuclear fusion is achieved, it would offer the potential of generating an almost inexhaustible source of clean energy. However, to date progress has been held back due to the complexity of the engineering challenges. Many countries are involved to some extent in fusion research including the European Union, the US, Russia, Japan, China and Brazil (World Nuclear Association, 2020). In short, if nuclear fusion can be achieved on earth it would be a potential game-changer as a solution for tackling climate change. However, if nuclear fusion were developed with it would come the need for the development and implementation of appropriate governance and control mechanisms to ensure the responsible use of such an incredibly powerful energy source.

22 Fracking

Proponents of fracking have argued that it can be used as a bridging technology until renewable energy solutions are widely available. However, with the plummeting costs of renewable energy costs combined with safety concerns around fracking, these assumptions are increasingly being reassessed. Furthermore, even though fracking may have lower carbon emissions in core operations, the risk of methane gas leaks, not just at the time of drilling, but at any time subsequently, mean that the total lifetime emissions from fracking may actually be much higher than from conventional fossil fuel combustion.

In addition, it takes a lot of energy to run the fracking process itself–and this makes the carbon benefits marginal even if there are not any leaks. Furthermore, it may take years to get all the necessary approvals to allow fracking production by which time countries need to be well advanced in decarbonizing their economies. In short, due to the risk of GHG emissions from methane gas leaks as well as other significant limitations and challenges, fracking does not seem to have a significant role to play in decarbonizing the global economy.

Table 2 CO_2 emissions per passenger (kg) for different modes of transport

Mode of transport	CO_2 emissions per passenger (kg)
Car	36.6
Train	5.2
Coach	4.3

Source Written parliamentary answer Monbiot (2006)

23 Transportation

Moving now on to consider decarbonization options for transportation, the following table is an extract from a table in George Monbiot's book 'Heat' published in 2006 (Table 2).

According to the study above, the CO_2 intensity per person on a coach is only 12% of the intensity for cars with an internal combustion engine. Unfortunately, in many countries coach travel is not a viable option due to issues such as poor connectivity with other transport modes. However, investing in public transport, in a coach network, in well-connected cycle- and walkways and improving the connectivity between different transport modes has the potential to achieve rapid reductions in GHG emissions. However, though this may be feasible in theory, there are also important societal and human behavioural obstacles that would need to be overcome. Many people see a car as a status symbol and hence the notion of giving up owning a car and embracing public transport instead can seem counter-aspirational. In short, public transport offers significant opportunities for decarbonization but to decarbonize the transport system we will of course also need to decarbonize private vehicles and it is to these we now turn.

24 Electric Vehicles

An electric vehicle (EV), is a vehicle that runs on an electric motor. There are two basic types of EVs: all-electric vehicles (AEVs) and plug-in hybrid electric vehicles (PHEVs). An electric vehicle may be powered by electricity sources including battery, solar panels, fuel cells or an electric generator.

EVs are rapidly becoming popular due to improvements in the technology, reductions in costs and their environmental benefits. For example, EVs release no tailpipe air pollutants at the place where they are operated. EVs are charged with electricity mainly sourced at present from the regional electricity grid mix. Globally, most electricity is currently sourced from power stations using fossil fuels, though globally the carbon intensity of the electricity grid mix is reducing due to rapid uptake in renewables. Hence, for maximum climate impact, EVs should run on renewable energy. As a broad generalization, around 70% of the carbon footprint of driving an ICE is down to the fuel and the rest from the emissions involved in manufacturing the car in the first place (IEA, 2020). Electric vehicles are responsible for fewer emissions in use even if the electricity has all come from a coal power station, because their engines are so much more efficient than ICEs.

EV technology has improved dramatically recently and sales are now starting to grow rapidly. EV sales in the 3 main markets of North America, Europe and China are now starting to increase rapidly. At the end of 2020, EV market share of new car sales was as high as 54% in Norway for the full year and 67% for December (The Guardian, 2021). Whilst in the larger economies in H1 of 2020, France led with 9%, followed by the UK and Germany both with around 8% and China with 4% EV (2021). The global EV fleet was set to reach 10.5 million vehicles by the end of 2020 (Ibid). Quarterly EV sales of Tesla reached around 100,000 vehicles globally by the end of 2020 and Elon Musk, their CEO, is targeting annual sales of 20 million EVs by 2030 (Business Insider, 2020). Most of the other major car manufacturers now have EV models and are investing heavily in this area. Indeed, linked to the global decarbonization and net zero agenda, many countries now have phase out plans for diesel and other ICE vehicles, which are currently mainly between 2030 and 2040. Hence, there is now a clear direction of travel away from ICE vehicles towards clean transport and for light vehicles this transformation is currently focused on electrification. For heavy vehicles, green hydrogen may be an effective decarbonization solution. Green hydrogen is discussed later on in this chapter.

25 Aviation

Aviation, and also shipping, is at a much earlier stage in decarbonization than much of road transport. Pilot studies have been successfully conducted for small-scale electric planes but, as of early 2021, there have not been any commercial flights using electric planes. Some companies are investigating the potential of using hydrogen, but this is similarly at a very early stage. More advanced is the use of some biofuel blends to replace jet fuels. However, use of biofuels needs to be carefully managed since only under certain conditions may they be sustainable. Biofuels are discussed further in the next section.

26 Biofuels

Biofuels are fuels produced from biomass. Biofuels can be produced from plants or from waste that had a biological origin such as from agriculture. The two most common types of biofuel are bioethanol and biodiesel. If the biomass used in the biofuel production can regrow quickly, the fuel is normally considered as being a form of renewable energy. Extreme care is needed in using biofuels as without proper planning there is a real risk that any emission savings from biofuel consumption will be more than offset by increases in emissions from elsewhere in the life cycle and that other severe negative externalities will arise. For example, if biofuels are sourced from palm oil grown in South East Asia or ethanol from the Amazon then there is a real risk that life cycle emissions will increase due to high emissions from rainforest being cleared to make way for growing biofuels. Similarly, using first-generation biofuels, whereby edible crops are used to make liquid hydrocarbons, risks exacerbating global issues around food poverty since indirectly this could lead to increases in food prices and increased risk of food poverty. Indeed, already around 1 billion people globally are malnourished or undernourished.

More attractive is the idea of using second-generation biofuels whereby liquid fuels are produced from cellulose, enabling high yielding energy crops to be grown, but only on marginal land that cannot be used for food agriculture so as not to exacerbate global issues connected to food hunger and deforestation. However, the use of marginal land still requires detailed analysis in order not to threaten other ecosystem services and exacerbate what is already a global crisis of biodiversity loss.

Some experts propose the use of algae as a biofuel since micro-algae grow incredibly fast and are responsible for 40% of the world's current levels of carbon fixation (Berners Lee, 2019). It is estimated that there could be millions of algal species that could be used to help develop efficient biofuel resources. However, the technology is at an initial stage and there are obstacles to overcome ranging from species selection (breeding and genetics) to refining and processing of oils (Hannon et al., 2010).

27 Renewable Hydrogen

Hydrogen is already an energy carrier with a well-established global market but at present, around 95% of hydrogen production comes from fossil fuels (Hydrogen Production). However, hydrogen can be produced from a wide variety of sources, including renewable sources, such as solar and wind, tidal and wave energy and then stored safely in the form of hydrogen gas. Recent technology improvements are starting to make renewable or 'green' hydrogen much more feasible. Renewable hydrogen is potentially extremely significant in decarbonizing the world's energy supply since it can be safely stored and transported as zero-carbon hydrogen gas, renewable energy would then become permanently available without intermittency problems. Thus, it also offers the potential to help decarbonize hard-to-electrify sectors such as long-distance transport and heavy industries like cement and steel and replace fossil fuels as a zero-carbon feedstock in chemicals and fuel production. Green hydrogen also offers significant potential for decarbonizing heat, which is at a much earlier stage of decarbonization than power.

Due to its potential as an energy carrier, renewable hydrogen offers countries and regions that are rich in renewable energy resources such as Australia and North Africa the potential to supply other regions of the world that do not have such natural resources. However, to realize the potential of renewable hydrogen, numerous challenges will need to be overcome including issues around managing safety, developing new and retrofit infrastructure and the development and implementation of a stable long-term policy landscape to accelerate investment.

In addition to green hydrogen, other studies are focusing on using carbon capture and storage (CCS) to decarbonize hydrogen produced from fossil fuels ('blue' hydrogen). Many experts argue that blue hydrogen is essential, at least in the short-term, as a bridging technology until green hydrogen is widely available at scale. However, this view is contested by many; as noted, blue hydrogen relies on CCS, which is still in its infancy. Another risk to blue hydrogen is in terms of the potential for significant upstream methane leakage, and hence potentially extremely high GHG emissions, from CCS installations.

28 Carbon Capture Storage (CCS)

CCS involves stripping carbon out of fuel before or after being burnt. CCS facilities at the point of combustion can be important for certain large sources of combustion whilst fossil fuel persists in the energy mix. CCS technology has been used for decades to purify natural gas and other gas streams at industrial facilities.

For CCS to be viable, however, it is essential that the geology is favourable and suitable geological reservoirs include old oil or gas fields, saline aquifers and unmineable coal seams. In addition, CCS is essentially viable in certain areas for new builds only as it is difficult to retrofit power plants with CCS. Power plants tend to have economic lives of 30–40 years and hence for CCS to contribute effectively to global decarbonization goals it needs to be scaled up rapidly.

An inherent problem, however, with using CCS with power plants is that extra energy is required to run the CCS processes, with estimates ranging from 14–40% based on the type of plant (Rubin et al., 2005), meaning that the electricity generation would become much more expensive than for a plant without CCS, at least when externalities are excluded. The additional CO_2 generated from burning the fuel to power the plant can also be buried and studies indicate a net carbon saving of 80–90% compared to a plant without CCS (IPCC, 2005).

CCS includes Integrated Gasified Combined Cycle (IGCC) methods that are used to transform coal into a gas and then mixing it with oxygen to power a gas turbine. A second method is to burn the coal in oxygen-enriched air and recycle the exhaust gases back through the combustion chamber to create an exhaust gas that is predominantly CO_2. The CO_2 then needs to be separated out from the materials it was mixed with and then compressed into a liquid for transport and subsequent storage in geologically suitable strata where it can remain for millions of years.

To date, however, CCS investments have been relatively minor with many focused on prolonging the life of fossil fuels. These have included injecting CO_2 into oil wells to enhance oil recovery or to capturing CO_2 emissions from the smokestacks of coal-powered power plants. According to the 2019 Global Status of CCS report Global (2020), there are now 51 commercial-scale CCS plants across the Americas (24), Europe and Asia-Pacific (both with 12) and the Middle East (3). Of the 51 facilities, 19 are operational, 4 are under construction and 28 are in different phases of development. The report states that, to date, 260 million tonnes of anthropogenic CO_2 emissions have been permanently stored and the global capture and storage capacity of CCS plants in operation or under development globally is around 40 million tonnes per annum. Nevertheless, CCS is seen as viable at a large scale from CCS 2030 onwards (Budinis, 2018).

CCS has the potential to help significantly reduce emissions from major energy-intensive industries such as steel, cement and chemicals production. Advocates state it is one of the few technologies that can deliver negative emissions on a large enough scale to support global decarbonization goals. Nevertheless, as already noted, to date many of the CCS plants have been used to inject the captured CO_2 into oil fields to enable further oil extraction.

CCS is likely to be politically attractive and popular with many industries as it could allow the use of abundant national fossil fuel reserves that would otherwise need to be left in the ground and to preserve some of the largest emission-intensive industries.

In addition to CCS, CCUS (carbon capture usage and storage) technologies, focus on the use of CO_2 after its capture and transportation as a resource to create valuable products or services, providing the foundation for carbon removal or negative emission technologies, some of which are discussed later on in this chapter.

29 Biological Carbon Capture and Storage (Bio-CCS)

Bio-CCS is a process whereby waste biomass is burned and then the resulting CO_2 is captured and stored at depth in rock strata. The amount of carbon generated by burning biomass depends on many factors. However, around half of dry matter is carbon, meaning it would be necessary to burn at least 2 billion tonnes of bone-dry feedstock such as sawdust to generate 1 billion tonnes of carbon storable as CO_2 (Ibid). The costs for this currently immature technology are likely to be expensive though they are likely to reduce as the technology improves.

In addition, there are many other biological carbon removal technologies, some of which are explained later in this chapter.

30 Agriculture

Globally, food production is responsible for around a quarter of global emissions (Ritchie, 2019), principally due to land use change (e.g. deforestation), methane emissions from cattle, emissions from fertilizer usage and soil losses. Due to the global population increasing rapidly and becoming more affluent (and hence leading to dietary changes and consumption of more food, including more carbon-intensive food such as red meat), under the current trajectory emissions and other negative externalities from agriculture are set to rapidly increase. Hence, solutions for tackling emissions from agriculture are essential and there are a wide range of emerging solutions. Many revolve around regenerative agriculture whereby the focus is on conservation and rehabilitation of the topsoil, which offers the possibility of greatly improving carbon sequestration whereby potentially huge amounts of carbon can be stored in the soil, amongst many other benefits. Carbon is stored directly in soil such as through humus, but the amount varies greatly due to land use. For example, cell grazing whereby a herd moves from one area to the next after a short period of time (hence imitating the grazing routines of the ancient roaming herds) may result in increases in soil carbon. A key issue for using soils as a decarbonization strategy has been the lack of precise data to measure how much carbon is or can be stored in different types of soil. However, recently there has been progress in this area with one recent public announcement on a new digital technology that would allow the amount of soil carbon in a field to be mapped on a real-time basis to a level of precision 10,000 times better than traditional methods (Jonnes).

There are also emerging technologies that focus on replacing meat and even plant foods with substitute foods. For example, the Finnish company, Solar Foods, has pilots focused on making edible proteins from electrolysis based on renewable energy and without the use of any animal or plant inputs. According to the company, factories for solar foods could be built in areas that are not suitable for food production with current methods, but that have solar or wind energy potential, such as the deserts or potentially even space.

Solar Foods' protein product is made by using electricity, sourced from renewable energy, to extract carbon dioxide from the atmosphere and combining it with water, nutrients and vitamins. Products such as solar foods could potentially have a major impact on food production (Monbiot, 2020), since potentially agriculture would no longer be needed to produce food and the land freed from agriculture could be reforested or allowed to rewild and hence converted into carbon sinks. Though the technology is at an initial stage, the potential rewards from solar food are so immense that they warrant major further research to better understand and corroborate the benefits.

31 Geo-Engineering

31.1 Direct Interference with Sunlight–Solar Manipulation

The most widely discussed geo-engineering proposal to date is the idea of injecting sulphur into the stratosphere in order to reflect sunlight back to space and allowing the Earth's surface to cool. The concept has been inspired by what already happens naturally when volcanoes erupt, injecting huge amounts of dust and sulphur into the stratosphere. However, this also highlights many potential major risks concerning implementation including in terms of health and safety, ethics and governance. Recent studies suggest direct financial costs for the core operation of injecting the sulphur as being in the range of $ 2–8 billion (McClellan et al., 2012). It is important to note that these costs do not price in externalities, such as might result from changing rainfall patterns, crops not being able to grow and from changing the amount of sunlight reaching the earth's surface. Indeed, a study in 2014 found that all geo-engineering proposals that block the sun's rays are likely to affect rainfall and could negatively impact billions of people due to changes in rainfall pattern such as with the Indian monsoon (Shukman, 2014). Furthermore, stratospheric sulphur aerosols, as is known from studying volcanic eruptions, destroy the ozone layer and can cause major risks to humans including diseases such as cancers.

An important current project is the UK's SPICE project (Stratospheric Particle Injection for Climate Engineering), which is investigating the effectiveness of Solar Radiation Management (SRM) to offset the effects of greenhouse gas increases by causing the Earth to reflect more radiation from the Sun. The project is rightly considered just as a short-term solution to buy us some time for reducing our emissions and tackling the root problems behind global climate change and its impacts. Since unless greenhouse gas emissions are reduced and ultimately reversed, other material impacts from carbon emissions will continue to grow such as in terms of ocean acidification. There is also the risk that an abrupt termination of stratospheric sulphur injections could result in rapid warming.

It is also important to note that volcanic eruptions can be used as a useful partial indicator but that there are important potential differences between geo-engineering and volcanos and hence impacts may differ. As one example, anthropogenic sulphur particles would be much smaller than those from volcanic eruptions and consequently it is uncertain how the sulphur would interact with the atmosphere (Crutzen, 2006).

Other geo-engineering proposals include injecting highly reflective nanoparticles in the atmosphere or by adding other materials such as soot particles (Keith, 2000). However, soot is carcinogenic. In summing up though, all geo-engineering solutions should be viewed as short-term solutions as they fail to deal with the basic problem of too much atmospheric carbon.

32 Carbon Removal Solutions

A report by the American Academies in 2015 on CO_2 removal noted that reducing CO_2 concentrations by 100 ppm (in order to return the atmospheric conditions close to what they were before the start of the Industrial Revolution) would require the removal of 1,800 billion tonnes of CO_2 (480 billion tonnes of carbon) (National Research Council, 2015). According to the IPCC, in order to avoid the worst impacts of climate change, humanity needs to remove around 10 billion tonnes of carbon dioxide from the air every year by mid-century (Rogelj et al., 2019). Removal methods can be split into 2 main categories: biological and chemical solutions and many of these systems involve reinforcing the Earth's systems. A key problem faced by all efforts to draw CO_2 out of the atmosphere is that if successful, large amounts of CO_2 will enter the atmosphere from the ocean as the systems move to equilibrium, which would at least partially offset the impact of the intervention technology.

33 Biological Carbon Removal Technologies

Biological methods are based on the removal of carbon from the atmosphere or oceans via photosynthesis, and then storing the captured carbon in a variety of ways—from living forests to charcoal and plastics or locking it deep in the Earth's crust. The energy required for the biological processes is essentially free as it is derived from photosynthesis, which in turn was provided by the sun's energy. Though an important advantage, it also means that the rate and volume of carbon that can be captured through biological pathways are dictated by the process of photosynthesis, which is highly reliable but relatively inefficient. For example, photosynthesis only uses 1% of the available solar energy as opposed to solar PV, which is currently up to around 20% efficient.

Another important limitation is that the biosphere is already under great strain due to extensive deforestation, pollution and species extinction. As a result of the increasing strain upon it, the climate mitigation capacity of the biosphere is at increasing risk of being compromised.

Clearly before any intervention, biological or chemical, a careful assessment is required of not just the potential positive impacts but also of the negative impacts of externalities. For example, planting tree monocultures has been linked to negative impacts such as being detrimental for biodiversity, disease and vulnerability to extreme weather events. For example, as the world warms and extreme weather events become more frequent and severe, areas of vegetation that are degraded and/or impoverished in terms of native biodiversity will be at increased risk. Hence, the impacts of global warming should be modelled down to the local level in order to identify the areas that should be set aside for reforestation or rewilding.

34 Afforestation

Trees, indeed, all plants, grow by taking in CO_2 and around half of their dry weight is derived from atmospheric carbon. As climate change gathers pace in the coming decades, rates of carbon accumulation will change. However, whilst some forests will grow more slowly or even die, others will probably grow faster due to the fertilization effect of more carbon dioxide in the air, an existing phenomenon sometimes called global greening.

Due to rampant deforestation in recent decades, there is clear scope for potential carbon sequestration through restoration. Indeed, a recent study indicated that only

27% of global deforestation over the period 2001–2015 had resulted from deforestation for permanent land use change (the rest being due to forest fires or temporary land change) (Curtis et al., 2018).

Afforestation can play an important role in contributing to climate change but as context, planting trees every year over an area the size of Greece (around 150,000 km^2) over a 50-year time period would allow us to remove around 1 billion tonnes of carbon. Furthermore, the trees must survive for at least 100 years for the carbon to stay out of the atmosphere.

Though reforestation may bring other benefits such as being linked to ecotourism, improvements in water catchment protection and reduced erosion, there are also other potential side effects. Studies have highlighted the risk of increased global warming in certain areas due to an increase in the earth's albedo due to widescale tree planting at scale. This is because trees absorb more heat energy than other surfaces such as paler grasses (Oregon, 2011). As a result, the increased heat absorption at the surface may offset, at least partially, the increased carbon drawdown from the trees.

When it comes to tackling climate change it is clear there is a wide range of solutions that are needed. Clearly, planting trees can play an important role. However, it needs to be done as part of a well thought-out strategy and recent research by Montague (2020) has made clear that in many cases it may be preferable to let nature take its course and to promote rewilding as we'll now discuss in the next section.

35 Rewilding

Different to planned interventions such as afforestation is the concept of rewilding. Rewilding is arguably an inspirational way of restoring wild nature that focuses on allowing natural processes to reshape and enhance ecosystems so that we create spaces where nature and people can thrive in harmony.

Across the world, there is growing recognition that the restoration of wild nature is a critical, cost-effective, immediate way of tackling climate change, reversing biodiversity decline, and providing many benefits such as protecting us from flooding and coastal erosion, reducing wildfire risk, enhancing human health and wellbeing and driving economic growth. By enhancing the functionality of natural ecosystems, rewilding can also reduce the risk of infectious diseases, such as COVID-19.

Advocates of rewilding maintain that active tree planting is only needed where seeds are completely missing, and tree species cannot come back on their own. In such cases it should be done as natural as possible, providing new seed sources to then stimulate natural regeneration.

A study by Cook-Patton et al. (2020) shows that the potential for natural forest regrowth to absorb carbon from the atmosphere and fight climate change is far greater than previously estimated (Conservation, 2020). The study shows that estimates of the rate of carbon accumulation by natural forest regrowth are much higher than had been previously estimated. The study showed that whilst there were huge variations for a wide range of reasons depending on factors such as climate and soils, natural regeneration can capture more carbon more quickly and more securely than plantations. The study is the most detailed attempt yet to map where forests could grow back naturally, and to assess the potential of those forests to accumulate carbon.

The study identified up to 1.67 billion acres that could be set aside to allow trees to regrow. This excludes land under cultivation or built on, along with existing valuable ecosystems such as grasslands and boreal regions, where the warming effects of dark forest canopy outweigh the cooling benefits of carbon take-up. Combining the mapping and carbon accumulation data, the study estimates that natural forest regrowth could capture in biomass and soils 73 billion tonnes of carbon between now and 2050, making it the single largest natural climate solution.

In many parts of the world, forests have been expanding, linked in part to a global trend of urbanization and depopulation of many rural areas. For example, estimates suggest that some 6.7 million acres of Atlantic Forest in the USA have naturally regenerated in this way since 1996 (Pearce, 2020). The Brazilian Atlantic Rainforest has also expanded in recent years (Ibid). In Europe, forest cover was reported as 44% in a 2009 study by the UK Government and studies have reported that the amount of forest has been increasing since the mid-twentieth century (FAO 2011; EU Woodland (2009)) due to land abandonment of many agricultural areas. Furthermore, this trend is expected to continue over the next few decades (van Vuuren et al. 2006). In a study of Poland, Slovakia and Ukraine, it was found that 16% of farmland was abandoned in the 1990s with much of the land being recolonized naturally by forest (Kuemmerle et al., 2008). Whilst in Russia, an area of former farmland around four times the size of the UK has been recolonized by forests (Pearce, 2020).

Whilst much of the focus, and the preceding discussion, is on solutions with forests, preserving and restoring other ecosystems is also extremely important for tackling climate change as well as many other issues such as biodiversity loss. To give just one example, wetlands are especially effective at capturing CO_2 from the atmosphere. Wetland plants grow fast and the oxygen-depleted conditions in many wetlands are ideal for storing carbon. Unfortunately, the world's wetlands, such as mangroves and saltmarshes, have been severely degraded and many have been converted to dry land for a range of land uses. Nevertheless, some degraded wetlands could be restored through the amount of carbon that could be stored, the costs and for how long remains highly uncertain.

36 Wood Chemistry

Before the oil industry became so dominant, many of its products were being generated from wood through the process of pyrolysis including a wide range of fuels, solvents and dyes. Due to the climate crisis, however, there is now renewed focus on wood chemistry and wood-derived products and companies around the world are starting to experiment with this technology again. As an example, methanol, used extensively as a transport fuel, can be obtained from food products such as corn. However, when derived from first-generation biofuels like these, there is at best a marginal carbon benefit over fossil fuels and they can even exacerbate other negative externalities such as deforestation and poverty. However, methanol made with second-generation technologies made possible with wood chemistry is under development and would allow methanol to be derived from cellulose, which would result in a much greater carbon benefit as tree farming requires fewer fossil fuels than growing corn (Galebach et al., 2018).

In terms of tackling climate change, the most important wood chemistry product concerns the production of biochar. Biochar is a relatively pure, mineralized form of carbon made by heating any biomass without oxygen. All the cellulose, lignin and other non-carbon materials gasify and are burned away. What remains is pure carbon—40% of the carbon originally contained in the biomass. The process requires little energy and is a carbon-negative technology as it allows for long-term storage of carbon that was captured from the atmosphere by plants. Biochar can take many forms, depending on a range of factors including what it is made from and the temperature during production. Whilst some forms of biochar are beneficial for certain soil types, other forms, especially those made at high temperatures can be toxic.

At present, the biochar industry is mainly comprised of small businesses in Europe and North America where biochar products are sold for local small-scale needs such as gardening (Ibid). Barriers to entry include a lack of awareness and hence demand for the product and access to financing. In addition, accurately estimating how much carbon can be sequestered, and for how long, cannot yet be determined due to a variety of factors such as the soil type the biochar is stored in.

Since the biochar will degrade over time, more biomass will be needed than the carbon that can be sequestered from it. Although the rate of biochar degradation will vary based on factors such as soil and moisture conditions, even under optimal conditions only a part of the carbon fixed as biochar during the pyrolysis process will be sequestered for more than a century. In short, though developments in biochar technology have improved rapidly in the last few years, biochar is currently only a marginal solution to climate change. In terms of potential downsides, it would be important to only use biochar from existing agricultural land rather than to set aside more land for growing biochar as this could exacerbate already major problems such as deforestation and hunger. In addition, much of the 'waste' that could be turned into biochar is already used on farms as animal feedstock, as fuel for stoves or as a soil conditioner. Nevertheless, in the developing world more than 10 billion tonnes of crop waste is burned annually in fields, releasing an estimated 11.2 billion tonnes of CO_2e, into the atmosphere. Hence, if this waste could be converted into biochar instead of burning it, potentially 3 tonnes CO_2 would be removed from the atmosphere for every tonne produced. The CO_2 could then, for example, be added to fields as a soil amendment so that the carbon would be permanently sequestered. In short, biochar is currently a promising yet immature technology that warrants much more investigation.

37 Seaweed

Though at an early stage, the cultivation of seaweed offers potentially enormous potential for decarbonization. Seaweed grows very fast and hence seaweed farms could be used to absorb CO_2 very efficiently and at a major scale. The seaweed could be harvested and processed to generate methane for electricity production or to replace natural gas with the remaining nutrients being recycled.

A study by N'Yeurt et al. (2012) estimated that growing seaweed could produce 12 billion tonnes per year of biomethane whilst storing 19 billion tonnes per year of CO_2 that result from biogas production. In addition, potentially another 34 billion tonnes of CO_2 could be captured if the CH_4 is combusted to generate electricity. Hence, theoretically, up to 53 billion tonnes of CO_2 could be removed annually from the atmosphere whilst also producing enough biomethane to replace all of today's needs in fossil fuel energy. These estimates are reported as being based on macro-algal forests covering 9% of the world's ocean surface, which would be similar to an area of over 30 million km^2 or over 3 times the size of the total land area of the USA.

However, if the estimates for CO_2 storage potential are accurate, just by itself seaweed harvesting would have the potential to capture almost our entire current level of global CO_2 emissions. Additional benefits would include a large increase in sustainable fish production, reduction in ocean acidification and increased ocean primary productivity and biodiversity. The CO_2 could potentially be stored in ocean floor sediments as discussed further on in this chapter.

However, covering 9% of the world's oceans with seaweed farms and then processing the huge amounts of resulting product is far from possible based on our current resources and capabilities. However, a lot of the technology required to achieve seaweed harvesting at scale already exists though currently at a small scale. For example, seaweed farming covers 200,000 acres just off the coast of China Seaseed Site. In addition, essential methane digesters are a basic technology that are already widespread in agricultural use for transforming waste and could easily be used on floating factories.

38 Chemical Carbon Removal Technologies

Chemical methods use the weathering of rocks, naturally or artificially, to capture carbon and then sequester the carbon. The chemical removal solutions, unlike the biological methods above, all require energy from human energy systems, either via electricity or fossil fuels. Hence, this is expensive and if renewable energy is not used, it will also be adding to the problem (through fossil fuel combustion) that it is trying to solve. Conversely, many of the chemical technologies offer the advantage of not only storing the carbon securely but also of creating something useful for humans in the process.

Over a billion tonnes of CO_2 is already sequestered naturally every year through rock weathering. In the 'enhanced' process, finely crushed basalt or dunite rock is thinly spread on the ground where it absorbs CO_2 at a faster rate with the potential for absorbing, according to a recent study, a massive 95 billion tonnes of CO_2 per year (Strefler et al., 2018), which is around twice global emissions at present. The huge downside is that dunite has traces of harmful minerals such as chromium and nickel. Alternatively, basalt can be used, but this is currently a lot more expensive, though it would have the added benefit of improving soil fertility by adding potassium (Ibid).

There are many potential chemical means of capturing and storing CO_2. For example, by exposing silicate rocks to weathering, CO_2 can be captured from the air by accelerating the weathering process that occurs naturally in nature by breaking large rocks into smaller pieces to increase their surface area and hence the rate of weathering. Another solution uses olivine, a mineral widely available at depth in the Earth's crust, which is transformed by naturally occurring chemical reactions into a variety of common rock types such as serpentinite. Olivine and serpentinite can absorb CO_2 over many years if they are ground into sand or soil that is exposed to air. However, though it can contribute to carbon removal as one of a range of solutions, huge amounts of rock would be required to sequester enough atmospheric carbon to have a planetary level impact on CO_2 levels. For example, it is estimated that up to around 5 billion tonnes of rock would be required to sequester a billion tonnes of carbon (Flannery, 2015).

Other rocks that can be used to capture CO_2 include lime produced from carbonate rocks such as limestone. However, lime production requires significant heat and huge amounts of rock to sequester significant amounts of carbon and hence would also be expensive. Another key challenge to overcome for enhanced weathering solutions includes finding a use for the material created from the process.

39 Direct Air Capture (DAC)

Direct air capture involves capturing CO_2 from the atmosphere, resulting in negative emissions as the captured CO_2 can be stored permanently in deep rock strata or used in the production of products containing CO_2 such as fuels, chemicals and building materials. According to the (IEA 2020), there are currently 15 direct air capture plants operating globally that in total capture more than 9,000 tCO_2/year, with a 1 million tCO_2/year capture plant in advanced development in the United States. The IEA estimates that direct air capture could capture almost 10 million tCO_2/year by 2030 but that this would require several more large-scale demonstrations to refine the technology and reduce costs of capture (Ibid).

The Swiss company, Climeworks, has developed a CO_2 capture device that can remove CO_2 from the air. Climeworks' technology includes CO_2 collectors powered solely by renewable energy or energy from waste. Air is drawn into the collector with a fan and the carbon dioxide is captured on the surface of a filter material inside the collectors. Once the filter material is full with carbon dioxide, the collector is closed. The temperature is then increased, releasing a very pure CO_2 stream that can be a valuable commodity. Grey emissions are below 10%, meaning that out of 100 tonnes of carbon dioxide capture from the air, at least 90 tonnes are permanently removed and only up to 10 tonnes are re-emitted. In November 2020, Climeworks signed agreements with both Carbfix, carbon storage pioneers, and ON Power, the Icelandic geothermal energy provider, to lay the foundation for a new plant that will help scale-up carbon removal and storage in Iceland. Climeworks' new plant will be able to permanently remove 4,000 tonnes of carbon dioxide from the air per year. Another firm, the Canadian firm Carbon Engineering, is focusing on capturing CO_2 from the atmosphere for uses including converting it into carbon-neutral fuel using renewable energy sources.

Prometheus Fuels, another new DAC company, is an American energy start-up developing tools to filter atmospheric CO_2 to produce commercially viable fuels using renewable electricity sources. According to the company, the first commercial fuel is due to be sold in California by the end of 2020.

40 Carbon-Negative Cements

Carbon-negative cements offer enormous potential as a carbon removal pathway for a sector that currently contributes an estimated 5% of global GHG emissions IEA (2009). At present most cement globally is produced by Portland cement, which is highly carbon-intensive since around 1 tonne of CO_2 is generated per tonne of cement.

Numerous ways of reducing emissions from cement manufacturing are being investigated such as using fly ash in the cement-making process though as it is a by-product from the highly carbon-intensive process of coal combustion, it does not seem viable as a decarbonization solution.

Much more promising though are methods that actually absorb and sequester carbon over long periods of time. For example, the US company Solidia Technologies extracts CO_2 from industrial waste and incorporates it into the cement. The company claims its cement can be used to produce superior, sustainable building materials that are cheaper than conventional Portland cement and that the technology has the potential to eliminate a minimum of 1.5 billion tonnes of carbon per year.[5]

Given that the cement industry is a major contributor to GHG emissions globally, carbon-negative cements could contribute meaningfully to global decarbonization goals if this technology could be incorporated at scale in new build. However, as an immature technology it is likely there would be resistance initially from industry before it was used to replace tried and tested conventional cement products.

[5] https://www.solidiatech.com/Solidia® – Making Sustainability Business As Usual^{SM} (solidiatech.com).

41 Carbon-Negative Plastics

Another use for CO_2 captured from the air is for storing in carbon-negative plastics. For example, Newlight Technologies in California, has invented and commercialized a carbon capture technology based on mixing air with methane and enzymes to form their carbon-negative product AirCarbon Newlight. AirCarbon can be used instead of oil to produce a range of plastics such as used in computer packaging and chairs and according to the company is already competitive with oil-based plastics in terms of both performance and price. Applications to date have included automotive parts and chairs.

In recent decades the science of biomimicry has become increasingly important and, in this field, pioneering companies are developing systems that some organisms, including some of the most primitive life forms, do naturally. For example, in a famous experiment in 1953, the American chemists Miller and Urey managed to create basic life forms in a laboratory in what they hypothesized might have been the way life started in the universe. Many years later, their experiment has inspired a new area of focus in terms of tackling climate change. By using water enriched with CO_2, rather than a mix of gases, through which to pass a current, scientists have been able to create long-chain hydrocarbons, the building blocks of fossil fuels (Flannery, 2015). Recently, the German company, Sunfire, has announced it has discovered a way of creating petrol and other fuels from water and CO_2[6]. Hence, this could offer the potential to create oil and other hydrocarbons from CO_2, water and electricity and hence without any emissions during the production phase. Their process involves producing steam and then treating it to remove the oxygen from the H_2O. The remaining hydrogen is then combined with CO_2 creating long-chain hydrocarbons.

Another innovative approach is being pioneered by Siemens where studies are looking at how to replicate photosynthesis (Schroder, 2014). Being able to replicate photosynthesis would allow many valuable materials to be created using only atmospheric CO_2 and water. Due to the complexity of the process, the Siemens team has focused on transforming CO_2 into complex hydrocarbons using electricity. The hope is that this process will be able to produce various chemicals such as ethylene and various alcohols. Potentially excess renewable electricity generation could be input into photosynthesis modules in order to produce valuable chemicals, which would help to reduce demand for petroleum and hence to reduce GHG emissions.

42 New Techniques for CCS

Earlier in this chapter, CCS technologies were discussed that focused on how carbon emissions could potentially be stored in engineering structures connected to fossil

[6] Sunfire. https://www.sunfire.de/en/

fuel plants. In addition, however, there has been some interesting, potentially groundbreaking, research that has focused on how anthropogenic carbon emissions could be stored at scale in planetary systems such as the ocean sea floor and the Antarctic ice caps. It is to these exciting new areas of research that we now turn.

43 Storage of CO_2 in the Ocean Crust

Recent studies by climatologists and geologists have also highlighted new potential for using CCS at scale whereby under the right conditions, CO_2 can be stored in either liquid or solid form. For example, a potential approach is for CO_2 to be stored in parts of the ocean crust whereby the pressure of the ocean waters above can be used to maintain the gas in liquid form or to lock it into the rock. Laboratory analyses have shown that if CO_2 is stored in marine sediments under at least 3,000 m of water, it stays in liquid form due to the enormous pressure of the overlying water column (Tohidi et al., 2010). Natural chemical processes in the water of the ocean sediments will then convert the liquid CO_2 into a solid as stable hydrates over time. CO_2 is prevented by the enormous pressure of the water above from rising towards the sediment surface, meaning that storage is stable and once the CO_2 has become a hydrate, it is locked into the rock permanently. Though not all ocean areas deeper than 3,000 m could be used for CO_2 storage, the potential is considered huge. For example, scientists estimate that the total CO_2 storage capacity within just the 200-mile economic zone of the US coastline is enormous and capable of storing thousands of years of current US CO_2 emissions Ibid.

Further research is needed but CO_2 storage in deep water marine sediments is considered one of the most promising solutions that could contribute significantly to emissions reduction globally.

44 Storage of CO_2 in the Antarctic Ice Cap

Another proposal is the potential to capture and store CO_2 in the Antarctic Ice Cap in a series of refrigeration chambers (Agee et al., 2013). CO_2freezes at –78.5°C at sea level and the average temperature over the interior of the Antarctic ice cap is –57°C. Hence, extra cooling of around –20°C or so would be required to cause CO_2 to fall out of the air and start to accumulate as snow (Flannery, 2015). The scientists estimate that air cooled with liquid nitrogen to below CO_2's freezing point would cause the precipitation of around 40 cm of CO_2 snow per day. The accumulated CO_2 could be stored in pits in the Antarctic ice and then covered with ice and snow to prevent its loss through sublimation on exposure to slightly warmer air. Agee et al. (2013). estimate that 446 refrigeration chambers could be powered by 16 1,200-megawatt wind farms in order to capture and store 1 billion tonnes of CO_2 per year (a reduction of 0.5 ppmv). Following the success of a prototype system in the

Antarctic, installation of all 446 plants for CO_2 snow deposition and storage would then be needed. The existing global Antarctic treaty provides the basis for scientific cooperation and international governance and in sum this is a solution that merits further consideration.

In terms of potential downsides, a potential risk is of CO_2 leakage from a warming ice cap. Climate modelling could be used to assess this risk though it is considered extremely unlikely even on a timescale of a thousand years and would be likely to materialize only in the event of a major global climate crisis. Though hard to estimate, it is likely that it would be extremely expensive to install refrigeration chambers on the Antarctic and that the project may not be feasible for several decades until the technologies improve and the costs come down significantly.

45 Digital Technology

Another major global trend is clearly in terms of the rapid development and uptake of new technologies related to areas such as digitalization, artificial intelligence and machine learning. Indeed, connectivity will be a key enabler for exponential technologies, which have huge potential for helping us to tackle climate change. Exponential technology has 2 main components:

(1) It's exponential, meaning that it doubles in capability or performance very quickly. Alternatively, its costs halve.
(2) It is a technology that is now at the point where its price-performance makes it possible to be incorporated into solving today's business problems in ways that were not previously possible due to higher costs. For example, previously due to high costs, drones were only financially viable in certain applications such as for military use. Due to plummeting costs in recent years, drones are now being used in a wide range of applications, including for helping to tackle climate change, as explained below.

An example of an exponential technology is the computer as the power of computer chips has doubled every 2 years or so since the middle of the last century. 5G is another exponential technology, which has data speeds 10 to 100 times faster than 4G. Ericsson estimates that the number of cellular connections will reach 4.1 billion by 2024 in its latest Mobility Report (Ericcson, 2020). With sensors in factories, smart cities and in our homes, 5G combined with AI has the potential to make our societies and economies radically more efficient and sustainable (Ekholm and Rockstroem, 2019).

Another breakthrough can be expected with electric and driverless vehicles. 5G is a crucial technology for safety, efficiency and reliability in this area. Driverless vehicles will accelerate a shift in the traditional business model of vehicle ownership towards mobility and transportation as a service. This means that fewer people will own a car but instead will order shared rides from driverless electric vehicles or catch a driverless bus.

Provided there is a robust policy framework and effective leadership, digital exponential technologies have the potential to play a major role in helping us to accelerate decarbonization efforts and the move towards a circular and lean economy.

The following section includes a summary of some of these technologies and examples of their application in helping to tackle climate change. The World Economic Forum estimated in 2019 that new digital technologies like Internet of Things (IoT) and Artificial Intelligence (AI) could help us cut GHG emissions globally by 15% or one-third of the 50% reduction required by 2030 for the world to be on track for reaching net zero by mid-century. Digital technologies have huge potential for a wide range of uses including for solutions in energy, manufacturing, agriculture and land use, buildings, services, transportation and traffic management Ibid.

46 Drones

Drones, also known as UAVs (unmanned aerial vehicles), can provide real-time precise data regarding changes in the earth's surface. They can also provide data from places that would be inaccessible or dangerous for humans to access, hence helping to improve safety. Examples of the applications of drones for tackling climate change and connected environmental challenges will now follow. For example, UK company Dendra plans to plant 500 billion trees by 2060 by using drones and AI. Dendra estimates its technology would enable governments to restore forests 150 times faster than planting by hand, and up to 10 times cheaper, which is of the scale needed to help halt and start to reverse the accelerating climate and biodiversity crises (Whiting, 2019). WWF estimates that we are currently losing more than 75,000 square kilometres of forests a year, including the carbon capture potential of those trees and that we need to be planting billions of trees annually.

Drones can also be used to measure surface reflectivity in order to show how much solar energy a landscape reflects. This can be useful for identifying areas suitable for tree planting where the change in surface cover from afforestation will not result in an increased albedo and hence potentially increased warming that would negate the carbon uptake from afforestation. They can also be used to pinpoint deforestation and areas of illegal logging, allowing law enforcement agencies to take swift action and hence restrict further loss and damage. They can also be used for assessing the most suitable locations for constructing new cleantech such as solar or wind; underwater uses to help monitor impacts of global warming on ocean ecosystems and also for monitoring changes in air quality.

47 Geospatial Technology

Geospatial technology, which give us an understanding of earth systems at a global scale, have enormous potential for tackling climate change. They can be used to map historical weather trends as well as future projections. They can be used to model land use against the GHG emissions from that area in order to identify carbon hotspots.

48 Internet of Things (IoT)

Internet of Things (IoT) technology can be used for real-time measurements of the planet. For example, they can be used to assess indirect effects of climate change such as indicated by changes in river levels, wind speed and land erosion. At the building level, sensors can be used to improve energy efficiency.

49 Conclusion

The threats from the climate and interconnected biodiversity crises are accelerating but so too are the opportunities. The tools to avoid a climate disaster now exist though many areas need more research and even more support in terms of deployment and upscaling. Another key issue is how to raise the finance and the extra capital expenditure required to install and maintain sustainable technologies. This clearly requires new sustainable financing mechanisms and the market for these is growing quickly. Indeed, since the first green bonds were launched in 2007 there has been a rapid increase in the size of the market for green financing and, as an example, up to 2019 there had been cumulative issuance of green bonds of USD 754 billion Climate Bonds (2019). Green loans have also been growing rapidly with 98% growth and 39 new green loans in 2019 Climate Bond (2020). The market for sustainable financial products is set to continue its rapid growth and, as it becomes more mature, there will be increased diversification, as we are already starting to see due to the C-19 pandemic, which has created demand for a range of social and pandemic financial instruments. There will also be increased standardization and scientific convergence and increased focus on sustainable financing solutions for transitioning brown sectors such as aviation, steel and cement.

Due to the accelerating climate and biodiversity crises, more negative shocks such as COVID-19 can be expected. However, their severity and frequency depend on our collective response to the current C-19 crisis and over the next few years. The time to act on the climate and biodiversity crises is now and for accelerating the transition to a sustainable, inclusive, circular and regenerative economy. Hence, though far more is needed, the recent acceleration in momentum towards decarbonization and cleantech has been encouraging. Indeed, at the time of writing in early 2021, China, the US, the

EU, UK, Canada, Japan, South Korea and South Africa plus many smaller nations that already collectively cover around 70% of the global economy, over half the world's emissions and over 75% of global fossil fuel export markets have announced net zero goals for 2050 or shortly thereafter, with many of these already enshrined in law. It is likely that this momentum will lead to more incentive and pressure on other countries to rapidly follow suit and commit to rapid net zero decarbonization. Rapid, urgent action really is needed and we all have a role to play. What we collectively do, or do not do, in the next few years will determine the fate of humanity and life on this planet for the coming decades and centuries. As the famous Roman Philosopher Emperor, Marcus Aurelius, is attributed with having once said: '*Quod in vita facimus, in aeternum resonat'* What we do in life echoes in eternity.

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Perspectives of Climate Change

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Abstract Climate change is one of the most severe issues the world is facing today, and it has placed humanity in a challenging position. In addition to causing irreversible harm to natural and human systems, climate change raises sea levels and temperatures, expands droughts, increases food insecurity, causes rain oscillations, and releases external contaminants into the environment. However, there are currently no effective mitigation mechanisms to cope with the implications of this global problem. In this context, this chapter aims to investigate and introduce the global climate change mitigation viewpoints. According to research, the only realistic and scientific strategy to mitigate this critical problem may be summarised as worldwide efforts to cut greenhouse gas emissions as quickly as possible. It is recommended that annual meetings be organised to examine the current situation, anticipate the future, converge viewpoints, and encourage underdeveloped and emerging nations to cut greenhouse gas emissions and adapt to climate change. The efficient use of energy, clean and renewable fuels instead of fossil fuels, and carbon emissions reduction are critical in lowering a country's carbon emissions. Many governments aim to shift as much of this obligation as possible to other countries to reduce their burden. In exchange, make use of the prospects for economic and industrial growth that may be achieved via low-cost fossil fuels. Consequently, it is proposed that each nation's contribution to greenhouse gas emissions is accurately calculated and that duties be established following the nation's greenhouse gas emissions share.

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1 Introduction

A growing number of scientists feel that environmental issues result from shifting human attitudes and the widespread practice of consumerism. On the other hand, others believe that it is the result of natural climate change that is unavoidable. Climate change has a variety of causes, both natural and artificial; while natural causes include factors such as earth rotation, continent movement, volcanic eruptions, and ocean water currents, man-made causes include factors such as population growth, urban development, industrial growth, deforestation, and increasing carbon footprints. In addition to the natural ecosystems, climate change has had an impact on human ecosystems. The magnitude of these consequences has been so tremendous that geoscientists have hypothesised a new geological epoch known as the Anthropocene (a period that marked the beginning of the significant effects of human activities on the ecosystems and geological structure of the planet) has begun. A few examples of evidence from this current geological period are the loss of the ozone layer, the devastation of marine reefs, species extinction, climate change, and global warming, among other things. The global climate change landscape has become so important that in addition to the world's scientific centres, the United Nations has established a particular working group called the Intergovernmental Panel on Climate Change (IPCC) to monitor and evaluate it. When it comes to climate change and its consequences throughout the world, it is critical to perform climate change research that will help us be better equipped to adapt to climate change and decrease its potential damage. The importance of climate change has grown in recent years due to the economic, social, and financial ramifications that it entails. The adverse effects of climate change can be so severe to human beings that it is regarded as one of the top ten most severe risks to human existence in the twenty-first century by the United Nations. According to the Intergovernmental Panel on Climate Change (IPCC), climate change and its consequences will continue until the end of the twenty-first century unless all greenhouse gases are eliminated now (IPCC 2007).

2 Global Climate Change as a Global Concern

The global climate is changing as a result of rising amounts of greenhouse gases in the environment. According to the Intergovernmental Panel on Climate Change, global temperatures have risen by around 0.3–0.6 °C, with the same forecast to climb to 3.5 °C by 2100. (Fig. 1).

According to the IPCC (2013) studies on the impact of climate change on different continents in the next decades, the following are the findings:

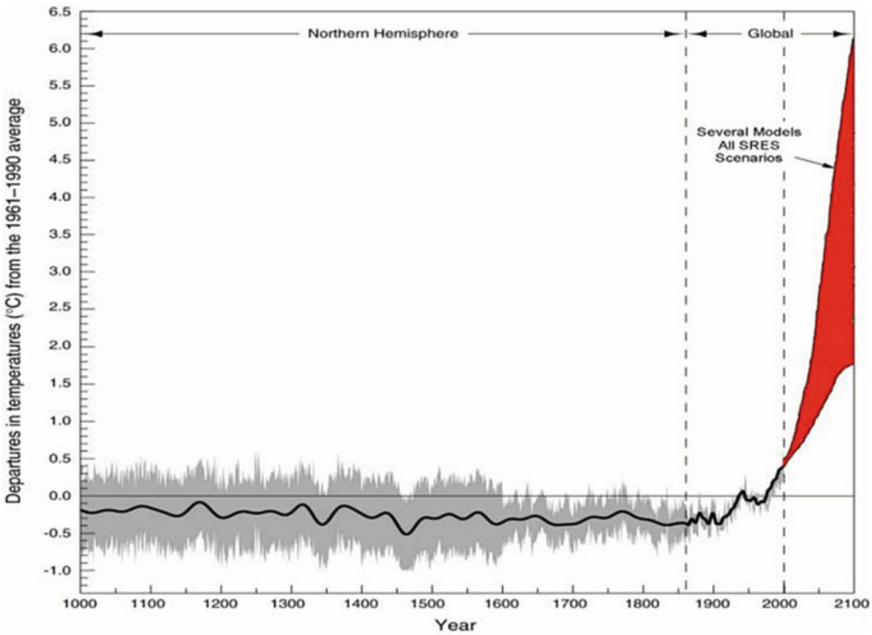

Fig. 1 The trend of global temperature increase in different periods (IPCC 2013)

- Severe drought will affect parts of Africa, with severe effects on household livelihoods and food security on a regional and national scale. Other portions of Africa will be devastated by destructive floods and water-borne illnesses, such as malaria and other infectious diseases, which will raise the death rate in those areas.
- Droughts, food and water shortages, and other natural disasters will become increasingly common throughout Asia. Flooding will occur in coastal regions due to increasing sea levels in some locations, resulting in damage to infrastructure and lives. It is a significant threat to the hundreds of millions of people who live along the Indian and Pacific Oceans coasts.
- Europe will be hit by disastrous floods, increasing sea levels, coastline erosion, and restricted availability of potable water, particularly in the southern hemisphere. Extreme heat will also hurt human health, grain production efficiency, and the quality of the air.
- Flooding, coral bleaching, and changes in the composition of coral reefs in the oceans are just a few of the effects of climate change that will significantly influence Australia's numerous industries and sectors. As sea levels rise in the Pacific and Indian Oceans, certain islands will perish, and others may become uninhabitable due to rising sea levels.
- In the semi-arid parts of Central America, there will be a reduction in the availability of potable water. In addition, floods and landslides will affect urban and rural regions at low elevations, reducing the amount and quality of food available.

- Increased storms, tornadoes, and floods (particularly in the river and coastal areas) are among the climate change consequences in North America that will risk public health and cause social systems to be disrupted. Drought conditions in the western United States are becoming increasingly severe, resulting in more frequent fires, deterioration of ecological integrity, and increased human mortality (IPCC 2013).
- There will be a reduction in marine biodiversity in the following years, and ocean acidification will accelerate this trend. Therefore, the ecological reversibility of coastal habitats will be diminished. The livelihoods of fishing-dependent communities would be severely harmed as a result of this. Table 1 summarised the future concerns about climate change concerning the different temperature values (Stern 2007).

Significant increase in the temperature and uneven distribution of precipitation are the most important features of global climate change that are limiting factors for sustainable development (Wang et al. 2015). The Earth's atmosphere is one of the shared global resources that individuals and businesses are responsible for protecting. Environmental laws in many nations do not place restrictions on the discharge of local and regional pollutants. Of course, it should not be forgotten that the recurring and negative repercussions of local and regional pollutants have been decreased to some extent due to the adoption and execution of mitigation initiatives. Until recently, however, there were few regulatory measures to reduce carbon dioxide emissions (as the main greenhouse gas). This pollutant has no immediate negative influence on the environment; but the buildup of carbon dioxide and other greenhouse gases in the atmosphere will have a considerable impact on world temperatures and climates, but the magnitude and timing of these effects are still up in the air.

Given that carbon dioxide and other greenhouse gases are continually accumulating on the Earth's surface, merely stabilising the release of these gases will not fix the problem immediately. For decades or even centuries, greenhouse gases persist in the Earth's atmosphere and continue to impact the temperature of the entire planet long after they are released into the sky. The only way to prevent greenhouse gases from continuing to accumulate in the Earth's atmosphere is to cut their emissions drastically. As a result, the amount of these released gases must be consistent with the Earth's absorption capacity. According to current estimates, human activity is responsible for somewhere between 20 and 50% of carbon dioxide emissions worldwide. It indicates that emissions from human activities must be decreased by at least 50% to 80% to keep up with the Earth's absorption capacity. To address global climate change, national and international policies must be developed that consider a wide variety of scientific, economic, and social challenges (Word Bank 2010). In light of the severity of climate change's consequences, it is in everyone's best interests to cut greenhouse gas emissions. It will not be enough for firms, communities, and nations to reduce greenhouse gas emissions if there is no consensus or law on the subject. As a result, climate change may be regarded as a global concern from the perspective of the common good, which necessitates collective action. Because this is a worldwide problem, only a strong international agreement that obligates governments to act on

Table 1 Concerns about climate change concerning the different temperature values

Type of impact	1 °C	2 °C	3 °C	4 °C	5 °C
Water resources	Disappearance of small icebergs in the Andes region and reducing access to drinking water for 50 million people	20–30% reduction in potential drinking water resources in some areas (South Africa and Mediterranean countries)	Risk of water scarcity for 1 to 4 billion people and severe droughts in southern Europe	30–50% reduction in potential drinking water resources in South Africa and Mediterranean countries	The disappearance of large icebergs in the Himalayas and damage to a quarter of China's population
Food and agriculture	Relative increase of agricultural products in different regions	5–10% reduction in grain production in tropical Africa	Risk of starvation for 150-550 million people around the world	15–35% reduction in agricultural production in Africa and complete destruction of agricultural products in some other regions	Increasing the acidity of the oceans will reduce fish stocks
Human health	Every year, at least 300,000 people pass away because of climate change-related diseases. Also, mortality is reduced at high altitudes	In Africa, 30–30 million people are exposed to malaria	Every year, 1.3 million people pass away due to malnutrition	More than 80 million people in Africa are at risk for malaria	Increasing diseases and inability of health care services to respond
Coastal areas	Increased damage caused by coastal floods	More than 10 million people will be exposed to coastal floods	More than 170 million people will be exposed to coastal floods	More than 300 million people will be exposed to coastal floods	Rising sea levels threaten megacities such as New York, Tokyo, and London
Ecosystems	At least 10% of terrestrial species are in danger of extinction and the risk of fire increases	4–15% of the species will become extinct	20–50% of the species become extinct and the Amazon forests are destroyed	Half of the tundra landscapes of the Arctic and coral reefs will be destroyed	Great extinctions around the world

public goods can prevent significant environmental effects from occurring (Karimi et al. 2021).

3 Options and Opportunities for Climate Change Mitigation and Adaptation in the Agriculture Sector

Climate change has had several negative consequences for several productive sectors, including agriculture; but, if the available possibilities and mitigation strategies are appropriately utilised, the resulting harm will be very little. Several mitigation measures are available for the agricultural sector, including farm management, animal management, natural resource management (soil and water), land-use modification, the use of renewable energy, and the most efficient use of energy resources in agricultural activities. According to Frelih-Larsen et al. (2014) and Underwood et al. (2013), the following are the broad mitigation approaches for lowering emissions in the international agriculture sector:

- N_2O emissions from agricultural soils and drainage should be prevented or reduced;
- Storage, processing, and use of chemical fertilisers should be reduced;
- Livestock sector is one of the primary producers of greenhouse gases such as CH_4 in the world, so proper livestock management practices should be followed to reduce their emission.
- Proper land and soil management to reduce CO_2 emissions.
- The machines which consume higher fossil fuels and increase CO_2 emissions should be appropriately optimised.
- The process of fertiliser production should be rationalised with environmental agriculture.

It should also be mentioned that there is no one-size-fits-all option for reducing emissions. However, a mix of these mitigation options can be employed in different sectors contributing to the gas emission.

As previously stated, the earth's climate became out of balance over the twentieth century, increasing global temperature (Dracup and Vicuma 2005). Droughts, floods, , heatwaves, and global warming are just a few of the consequences of climate change that have put the world in a state of emergency. Various places of the world experience different changes in temperature and precipitation, which do not always follow the same pattern (Clark et al. 2000). Climate fluctuation has had a significant impact on people's lives in the past. On the other hand, humans have contributed to climate change in the modern era through their actions. It has emerged as one of humanity's most pressing problems in the twenty-first century, as well as a possible threat to both natural and man-made surroundings (Jones 1998). The worldwide average temperature has grown by around 0.74 °C in the last 100 years, a significant rise. The winter's low temperature has increased at a greater rate than the maximum temperature of the summer (IPCC 2013). Evidence suggests that human activities have a greater impact on precipitation changes than rising temperatures (Liu et al. 2019). Precipitation has increased at higher latitudes and decreased at lower latitudes in general, while precipitation variability has risen practically everywhere (Asseng et al. 2015) and is increasing globally.

The IPCC report anticipates and warns of an increase in climatic and meteorological phenomena, such as droughts, floods, cyclones, and heatwaves, which can have serious consequences for natural ecosystems and human systems throughout the world (Tambo 2016). The Intergovernmental Panel on Climate Change (IPCC) has projected that climate change through 2040 (Feng and Fu 2013) will have a considerable influence on climate change resulting from rising greenhouse gas emissions and increasing industrial activity. Every year, around 40,000 million tonnes of carbon dioxide are released into the atmosphere due to industrial and agricultural processes. If the current trend continues, it is estimated that by 2040, this quantity would increase to 60,000 million tonnes. High greenhouse gas concentrations and rising global temperatures are expected as a result of this development. Furthermore, it is predicted that the Earth's temperature would climb by 3.5 °C by 2100 (Fig. 2).

From 1950 to 1970, the temperature decreased, and from 1970 until now, it has experienced an increasing trend. On average, global temperature has risen by one degree since 1950, which is more pronounced in European countries, especially southern Europe and the Mediterranean countries such as Italy, Spain, Greece, and southern France (Mohaqeq Damad 2000). Based on these climate model simulations, the average rainfall in the whole planet is expected to change significantly concerning space and time. The simulations also show that the number of storms and heavy rains will increase. Another consequence of rising global temperatures is the thawing of polar ice caps. This process will cause water levels to rise to 15 m in some areas such

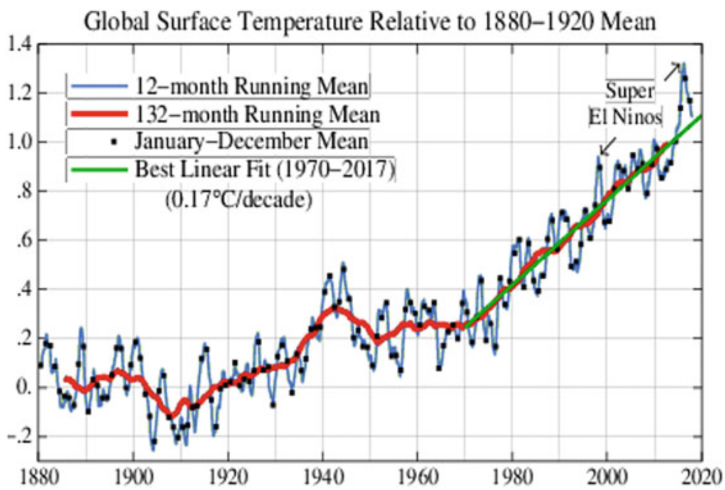

Fig. 2 Global surface temperature relative 1880–2020

as the Atlantic Ocean, especially off the coast of Europe (Iran Meteorological Organization 2017). In addition to submerging ports and destroying naval facilities, this advance of ocean water will cause saline water to flow into coastal rivers and even disrupt these countries' drinking water supply system. It is also argued that most of the world's freshwater wetlands may turn into saline wetlands. Such a change could severely affect the earth's natural environment. Another model states that the increase in billions of cubic metres of cold water caused by melting ice and floating pieces of polar ice will cause the earth's temperature to drop dramatically in a short period. Another pessimistic model predicts rising ocean water and floating chunks of polar ice, increasing pressure on ocean floor fissures. These events will move continental plates, create earthquakes, and lead to the infiltration of molten material into the ocean floor. The outcome of all these events will be the "instability of the earth", and under such circumstances, human life will be in grave danger. These changes will profoundly affect freshwater resources, coastal areas, biodiversity, forests and pastures, and even agricultural production (Yazdi 2018).

4 Climate Change Impacts

The importance of climate change has grown in recent years as a result of the economic, social, and financial ramifications that it entails. The negative consequences of this phenomenon on human beings are so terrible that it has risen to the top of the list of the ten most dangerous human variables (which also include poverty, nuclear weapons, food shortages, and other issues) in the twenty-first century. According to the Intergovernmental Panel on Climate Change (IPCC), climate change will continue by the end of the twenty-first century due to the 150-year persistence of carbon in the atmosphere. So the most important goal for the scientific community dealing with this phenomenon is to examine the implications of climate change on many elements of human existence and to develop comparable strategies for coping with these bad repercussions in the future (IPCC 2007). The major impacts of climate change are as follows.

4.1 Increasing Sea Level

Rising sea level is one of the most critical impacts of climate change, which occurs through increasing temperatures and melting glaciers and Earth's icy surfaces. Rising sea levels, even mild ones, lead to coastal erosion, submergence of the lands, increasing land and sea storms, salinisation of freshwater, and disappearance of coral reefs and sandy beaches. Therefore, it can pose a new threat to human life, species survival, agricultural land, facilities, and infrastructure (transport system, roads, piping systems, factories, buildings, and airports) (Pellinga and Uittob 2001). Coastal floods, coastlines' erosion, freshwater resources pollution, wetlands' flooding, and rising salinity of deltas are some of the actual issues that occur even with low sea level rises (Akhavan-Kazemi et al. 2019; Atalay 2014; Sweet et al. 2014).

4.2 Increasing Air Temperature

Investigations reveal that climate change has been the focus of various researchers over the past few decades, and many theories have been put forward about their origins, factors, trends, predictions, and impacts. Global warming due to human-induced activities is one of the leading environmental issues that has grabbed most scientific and political circles around the world in the last decade. Although industrialisation has brought progress, prosperity, comfort, and convenience to human beings, it has not achieved a global environment's glorious achievement. In other words, industrialisation has become a significant factor in destroying and disrupting the Earth. One of the influential factors in climate change is the increase in greenhouse gases (carbon dioxide, methane, etc.) due to human activities after countries' industrialisation (Jones and Warner 2016; Midgley et al. 2003; Park et al. 2017). According to IPCC, most global warming from the mid-twentieth century has been rooted in human-made greenhouse gases. Global warming could lead to the melting of glaciers and icy surfaces in the North and South Poles. Forecasts suggest that by 2030, all Arctic glaciers and by 2100, all mountains and Antarctic ice sheets will melt (Serreze et al. 2007). This will increase the air temperature as much as possible.

4.3 Development of Droughts and Food Insecurity

Drought is a decrease in rainfall compared to its long-term average. It causes an imbalance in water and water shortages, plant destruction, reduced water flow intensity, and surface water depth. This happens when the surface evaporation and water evaporation from plants are higher than usual within a certain period. Drought is the most severe problem for agriculture worldwide, and to combat this phenomenon, fertilising the clouds is a valuable but short-term method. In recent decades, drought has been more frequent among the natural disasters that have affected human life. Climate change will have adverse impacts on food resources and products that will lead to a sudden and sharp rise in prices of basic products and will substantially lead to political and economic turmoils (Hanjra 2010). Thus, climate change and its impacts on human food security have become an important issue (Fanta 2003).

Further, local households may face more restrictions on access to food. In other words, poor and vulnerable people, especially in developing countries, will suffer more from food insecurity than other groups (Devereux and Maxwell 2001). Climate change and its rebound impact on food security are already increasingly exacerbating in parts of the world. For instance, Africa and South Asia are known as the most vulnerable areas in terms of food security—a phenomenon defined as the physical and economic access of all individuals to nutritious and adequate food at any time and place; so that they can satisfy their nutritional needs to continue living a healthy and active life (FAO 2008). Climate change models show that the temperature and rainfall of all regions will be disrupted in the future, and as a result, agricultural production and food security will get affected. Also, the supply of meat and livestock products will be affected. Studies show that the agricultural productivity index will decline from 0.21 to 0.09 shortly (Liliana 2005). Global food reports (WFP 2016) show that agricultural productivity is slower than global population growth. Reports of the Food and Agriculture Organization (FAO 2011) show that the climate might affect the production and pattern of foods. Climatic events such as drought can endanger the livelihoods of rural areas, as rural areas in Asia are suffering from poverty (Skoufias et al. 2011). Combining these events ultimately leads to natural and human challenges, growing tensions, and exacerbating migration (Laczko and Aghazaman 2009).

4.4 Precipitation Changes

Climate change can disrupt rainfall patterns, and the frequently heavy rainfalls in the Northern Hemisphere (including North America, Northern Europe, and North and Central Asia) prove this claim. Rainfall is declining in most tropical, arid, and semi-arid regions of the world (the Mediterranean basin, South and West Africa, and northeastern Brazil) (IPCC 2007c). North Africa today is severely affected by climate change and its temperature and precipitation consequences. In recent decades, the global occurrence of precipitation has decreased by 20–30% in winter and about 40% in summer, with this problem as more severe and deadly in the western parts (Christiansen et al. 2007). In this regard, a particular concern in the Middle East is related to Egypt, with the depletion of the Nile River due to the decreased rainfall will severely affect agriculture. This problem will increase pressures on the population when combined with a rise in temperature, especially in warmer months. Similarly, in Russia's case, the melting of Arctic glaciers, in the long run, will extensively destroy the infrastructures in coastal areas. Furthermore, the unprecedented hail (more than 20 cm in diameter) that caused massive damage in the United States in 2010 is one more example of the rainfall disorders (IPCC 2007c) due to climate change.

4.5 Extraterrestrial Pollutants

Over the past few years, there have been emerging events that have no domestic origin. These events generally have no precedent of this magnitude in the given countries. Dust storms are a meteorological phenomenon that usually occurs during hurricanes in arid and semi-arid climatic zones globally, receiving less than 200–250 mm annual rainfall. Lack of rainfall and drought, strong winds, atmospheric circulation characteristics, climate change, loss of vegetation, and severe erosion are factors that can be effective in creating and intensifying such phenomenon. In Africa, the Sahara Desert is regarded as the most significant source of dust, releasing 700 million tonnes of dust into the atmosphere annually. The most important dust regions in the Sahara Desert include the Boudelle Pit and western Mali.

Moreover, southern Algeria and eastern Mauritania have also a significant role in the dust storms of the world (Viana et al. 2008). According to Kim et al. (2003), when the dust phenomenon occurs, nearly 30% of the dust is deposited near the source, 20% is released locally, and more than half is transmitted over long distances (Kim et al. 2003). For example, dust storms in sub-Saharan Africa have increased particle concentrations in southern Spain. The amount of these particles is 10–23 times the standard value (Wang et al. 2015, 2006). Scientific reports reveal that storms have a unique role in transporting dust particles. It is estimated that 0.5 to 5 billion tonnes of dust particles produced in the primary sources are transported to other regions of the world annually by storms (Escudero et al. 2007; Prospero and Lamb 2003).

In some cases, the number of dust particles increases from 2.6×10^6 to 26.1×10^6 particles per cubic metre. Particles smaller than 2.5 μm can affect the lungs and cause serious health problems for humans (Griffin 2007).

Studies show that the Sahara Desert is the primary source of dust storms in arid and semi-arid regions (particularly in the Middle East, Southeast Asia, and Mongolia). Northwest America and Australia are other important sources of dust. Northeastern Mauritania, western Mali, and southern Algeria are among Africa's most essential dust sources (Hong 1993) (Fig. 3). Furthermore, the primary sources of dust entering Iran are desert areas of Syria, Iraq, and the northern part of the Arabian Peninsula. But the role of the Sahara Desert in the meantime is considered very small (Fig. 4).

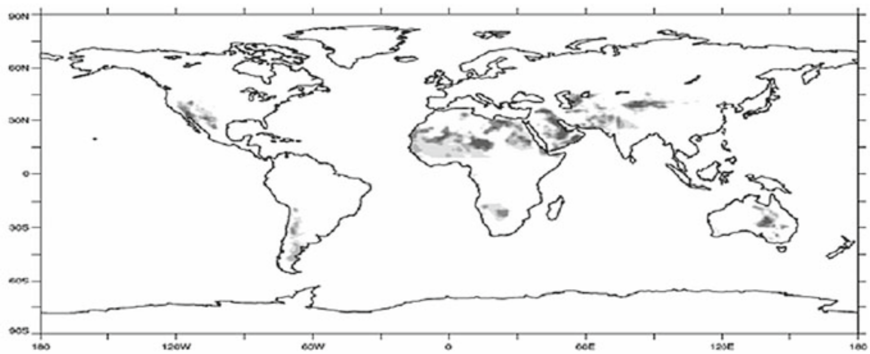

Fig. 3 The main dust-producing regions of the world

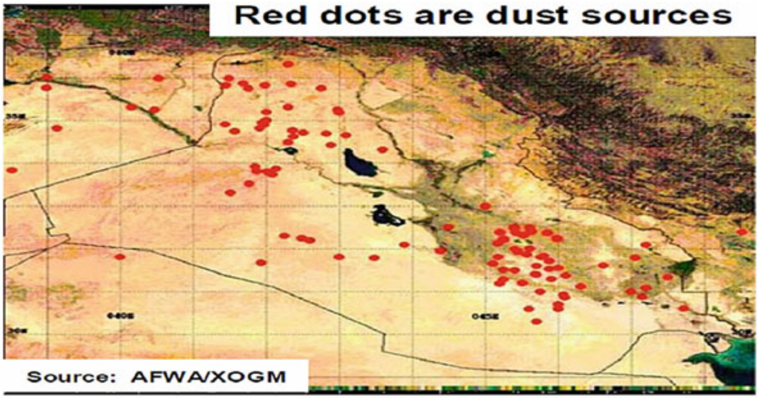

Fig. 4 The main dust-producing areas in Iraq

5 Climate Change and Its Impact on the Security of the International System

Climate change can pave the way for regional developments by creating challenges and opportunities, especially the escalation of conflict in the regions most affected by these changes. Thus, it affects international order and security in the long run and challenges regional security in some parts of the world. Africa, especially the Sahara Desert (due to extreme heat) and South Africa (due to severe lack of rainfall), are more influenced by climate change disasters than any other region. In other words, these areas feel the damage more severely and more widely than other areas (Akhavan-Kazemi and Veisi 2016). In general, the major climate change effects on security can be summarised as follows:

- Prevalence of infectious diseases;
- Immigration;
- Severe decline in agricultural production;
- Freshwater shortage and insecurity; and
- Increasing tension over energy resources;

6 Global Climatic Trends and Forecasts

Carbon dioxide is considered the primary basis for estimating and assessing the impact of greenhouse gases. Even the warming potential of other gases is measured based on this gas. For example, each molecule of methane and nitroxide is equivalent to 25 and 198 molecules of carbon dioxide, respectively, in global warming (IPCC 2006; Inventory 2010). Greenhouse gases are produced and absorbed by natural and unnatural greenhouse springs and wells shown in Table 2.

Table 2 Greenhouse gas springs and wells

Greenhouse gas	Source		Springs and wells	Life span
	Natural	Unnatural		
CO_2	Almost all organisms	Burning fossil fuels, deforestation, and aerobic fermentation of solid and liquid wastes	Oceans and forests	50 years
CH_4	Wetlands, termites, rivers and oceans, volcanoes, hydrates, and domestic and wild animals	Animal waste, rice paddies, consumption of fossil fuel, and solid and liquid wastes' anaerobic fermentation	Absorption by bacteria in the soil and chemical reactions in the atmosphere	10 years
N_2O	Microbial processes in the soil, ocean water, and vegetated soils	Chemical fertilisers, biomass burning and fossil fuels, industrial products, and human health	Soil uptake and photochemical reactions in the stratosphere	140–190 years

The Earth has become considerably warmer since reliable climatic information and data were recorded (Fig. 5). In the last 100 years, the average global temperature has upsurged by close to 0.7 °C (1.3 °F). Of the ten years that have been recorded as the warmest in the history of meteorology, nine have been recorded since 2000. In the Northern Hemisphere, 1983–2012 is regarded as the warmest 30-year period

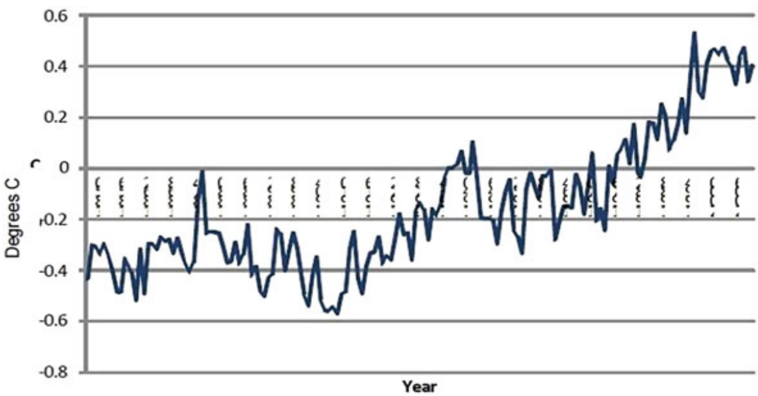

Fig. 5 Annual Global Temperature Abnormalities (°C), 1850–2012*. *Zero baselines indicate the average global temperature of 1990–1961*

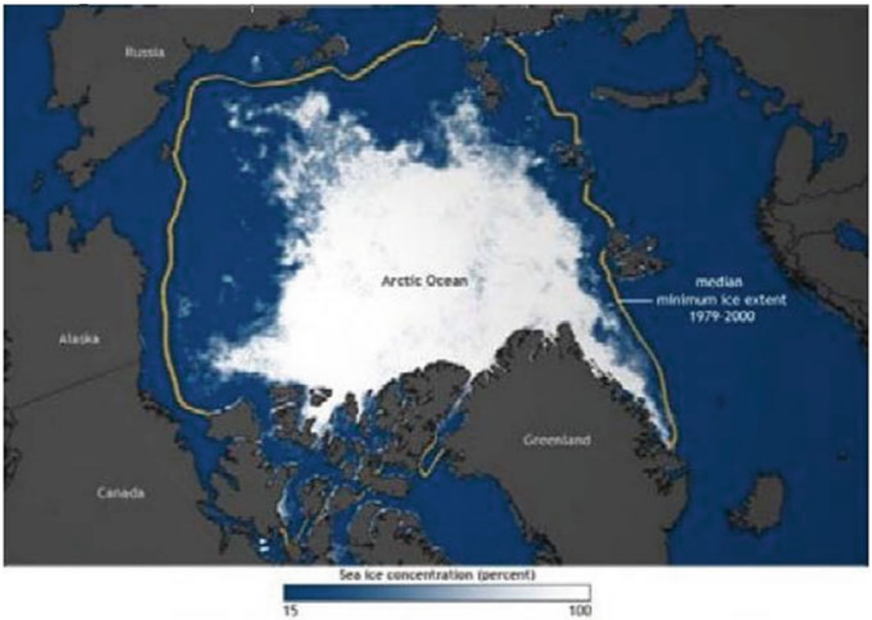

Fig. 6 Shrinking Arctic ice in the North (National Snow and Ice Data Center. Credit: Climate.gov.)

in the last 1400 years. Based on NOAA, 2014 was recognised as the warmest year since 1880. Ocean and land temperatures have risen more than one degree Fahrenheit above the twentieth century average.

Evidence shows that the heating rate (currently around 0.13 °C per decade) is rising, and not all areas are heated equally. The temperature rise in the Arctic and Antarctica is almost twice that of the world (Fig. 6) due to the melting of the Arctic ice; since the oceans, the surface reflects less sunlight than the surface of ice; this phenomenon is characterised as reduced albedo.

IPCC in 2013 argued that changes in the global water cycle are due to human activities and impacts. In other words, the evidence for human impacts has increased, which are likely to be the leading causes of the warming experienced since the twentieth century (IPCC 2013).

Rising temperatures have had a significant impact on ecosystems. In most parts of the world, icebergs are receding. Studies show that there were about 150 icebergs in Montana when the Glacier National Park (GNP) was founded in 1990. But in 2010, only 25 icebergs larger than 100,000 square metres were existent, and it is estimated that by 2030, there will be no more icebergs in the park. Climate change is leading to rising seas due to the melting of mountains and icy areas. Further, between 1961 and 2003, the oceans warmed by an average of 0.1 °C. Combining these two issues has led to an annual increase of 2 mm in sea level.

Increasing carbon dioxide in the atmosphere and rising temperatures lead to acidification of the oceans. According to NOAA, oceans have absorbed about half of the carbon dioxide that humans have produced since the industrial revolution. This has significantly decreased the intensity of global warming but has lowered the pH of the oceans, making them more acidic.

Recent reports in science show that the oceans have been acidifying rapidly for the past 300 years, with potential consequences on marine ecosystems. Coral reefs are more affected by ocean warming and acidification because they only form in a limited temperature range (Bradbury 2012).

Based on the climatic patterns and using future greenhouse gas emission assumptions, IPCC estimates that the average global temperature for the years 2081–2100 compared to 1986–2005 will exceed 1.5 °C (2.7 °F) and reach 4.8 °C (6.8 °F). Therefore, the Arctic will heat up faster than the global average, and the average onshore will be higher than the ocean. The possible temperature increases are demonstrated in Fig. 7, and the distribution of global warming for low-end and high-end scenarios is shown in Fig. 8.

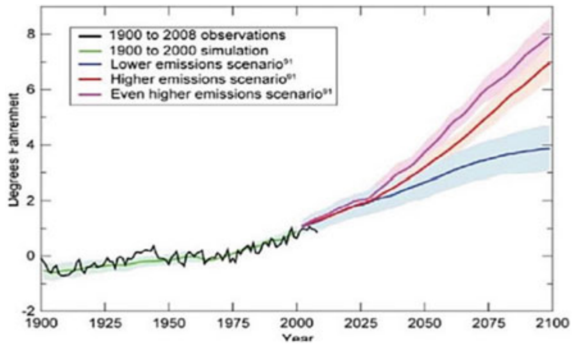

Fig. 7 Predicting global temperature trends by 2100

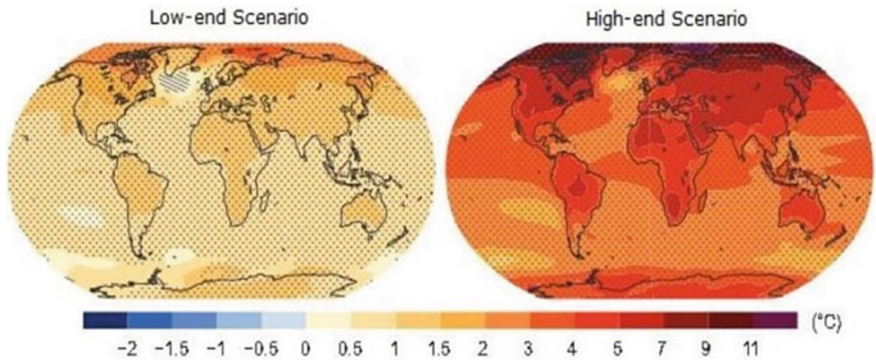

Fig. 8 Change in average surface temperature (1986–2005 to 2081–2100)

7 Mitigation and Adaptation Policies in the Field of Climate Change

Given that climate change occurs faster, mitigation and adaptation policies in this area should also be addressed in the long or medium term. Such an approach makes it possible to change climate policies in line with new technological innovations and economic development. The effectiveness of mitigation policies varies according to the countries' social, economic, political, and geographical capacities. However, the degree of success in adaptation and mitigation programmes is directly related to the practical application of climate guidelines by the executive agencies. In this regard, the climate policies of countries must provide guarantees for compliance with the laws. Otherwise, global partnerships to mitigate the effects of climate change will not succeed.

By going through the literature, two approaches to managing and mitigating climate change impacts can be identified: top-down and bottom-up. Top-down approaches are generally related to international agreements on climate change, e.g., the Kyoto Protocol and the Paris Agreement. Bottom-up approaches are mainly made at the national and regional levels with the participation of various actors. In bottom-up approaches, the "cooperation of actors" is a crucial factor in mitigating the impacts of climate change. Further, to minimise the effects of climate change, two instruments, including market-based and control regulations, are usually used. Market-based instruments refer to the subsidies and taxes systems related to greenhouse gas emissions. Conversely, control regulations include specific restrictions on carbon footprints or emissions. In this approach, climate change actors are forced to use environmentally friendly innovations in control regulations (Jaffe and Stavins 2009).

8 Summary

Over the past two decades, climate change has impacted many countries and regions of the world. This phenomenon's negative impacts in developed and industrial lands are less than in developing and underdeveloped countries. Because many developing and underdeveloped countries do not have the economic capacity to deal with the negative impacts of this phenomenon or build the necessary infrastructure for climate change. In recent years, some developing countries, like that of the developed countries, have accounted for the widespread use of fossil fuels (oil, gas, and coal) with China (28.21%), the United States (15.99%), India (6.24%), Russian (4.53%), Japan (3.67%), Germany (2.23%), Korea (1.75%), Iran (1.72%), Canada (1.71%), and Saudi Arabia (1.56%) as the largest producers of greenhouse gases in the world (Germanwath 2016). In this regard, the only practical and scientific way to reduce or counteract this natural phenomenon can be summed up in global efforts to reduce greenhouse gas emissions. Reducing greenhouse gas emissions and supplying energy from renewable and non-fossil fuels requires macroeconomic investments and new technologies in various fields. Optimising energy consumption, using clean and renewable fuels instead of fossil fuels, and reducing carbon emissions are the key strategies in reducing a country's emissions. These measures are accompanied by declining revenues and the need for investment, so governments are trying to avoid accepting responsibilities to reduce greenhouse gas emissions. In other words, many countries try to delegate this responsibility to other countries as much as possible, and in return, take advantage of opportunities for economic and industrial development using inexpensive fossil fuels. Therefore, it is recommended that each country's contribution to greenhouse gas emissions be precisely determined, and responsibilities are defined in proportion to their share in greenhouse gas emissions.

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