Politecnico di Torino

Master's Degree in Environmental and Land Engineering
Climate Change

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Environmental damage remediation, case study: Cengio and Saliceto Site of National Interest

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Summary

Abstract

The case of ACNA in Cengio has become an historic case regarding the detrimental consequences and negative impact on ecosystems that arise when industrial activities proceed without environmental compatibility standards, without proper regulations, controls, and management by the government and competent authorities.

The pollution and the repercussions of over a century of uncontrolled and environmentally incompatible industrial activities have affected an entire community, local economic activities, agricultural activities, their social structure, and the environmental and landscape heritage of an entire valley and its river.

The purpose of this thesis will be to describe the events that led to one of Italy's most significant environmental disasters, as well as analyse the components characterizing the impacts of ACNA industrial activities and pollution on the ecosystem, soil, the Bormida River, and the health of the residents in the surrounding areas of Cengio and Saliceto. Additionally, the Remediation Technologies will be presented and discussed, using the example of the remediation and environmental restoration carried out by ENIRewind in the Site of National Interest (SIN) of Cengio and Saliceto.

The thesis is divided into four central chapters. The first two central chapters will provide an overview of the main topics covered during the study course, including an overview of the issue of Climate Change. Starting with a description of the climate system as a whole, then the sectors, and the causes that have the greatest influence on the alteration of the planet's normal climate equilibrium, and also the consequences and impacts of climate change on the environment and human society will be described. Finally, possible future scenarios dependent on mitigation and adaptation actions undertaken in the present, short, medium, and long term will be presented.

In particular, the third chapter will analyse mitigation and adaptation technologies and strategies for climate change. Regarding mitigation, strategies and technologies related to the energy sector, renewable energies, sustainable and eco-friendly production strategies, the transport sector, and emerging technologies for mitigating, controlling, and reducing CO2 concentration in the atmosphere will be analysed. As regards adaptation, the main strategies will be described, including for example sustainable urban planning, water resource management, and sustainable agriculture.

The fourth and fifth chapters establish a link between climate change and the case study. As stated and confirmed by the reports of the Intergovernmental Panel on Climate Change (IPCC), which will serve as the main references throughout the entire thesis, ecosystems represent the largest natural barrier against the impacts of climate change in the coming decades. Therefore, the importance of safeguarding ecosystems plays a crucial role in facing climate change and is closely linked to the concept of sustainable development. For instance, industrial activities that, even if competitive in the market, still respect and protect the surrounding environment, something that was not realized in the case of ACNA's century-old activity. In this case, given

the unequivocal state of degradation and destruction of the ecosystem caused by industrial activity, remediation and restoration activities were and are still now necessary.

In particular, the fourth chapter will initially describe the relationship between ecosystems and climate change, which can result in a positive or negative feedback loop depending on the health of the ecosystems themselves. If ecosystems are degraded, compromised, or destroyed, they cannot fulfil their role as natural barriers against the impacts of climate change (which benefits not only the environment but also human society, for example considering the role played by riparian vegetation and forests in the case of extreme precipitation and flooding). Moreover, they become more vulnerable to the impacts of climate change, further degrading and continuing the negative cycle. Conversely, as stated in the scientific reports mentioned, a healthy ecosystem can mitigate the causes and effects of climate change, weakening them and thus being able to resist them while helping human society adaptation. This contributes to establishing and consolidating strong natural resilience to climate change.

At the end of the fourth chapter, guidelines for the maintenance, control, and restoration of river ecosystems will be described, along with the theoretical framework related to environmental damage, including analysis and evaluation criteria, methodologies, and strategies.

The fifth and final chapter will describe the case study of the Cengio and Saliceto SIN, starting with a brief description of the valley's ecosystem, the river, and the affected area. A chronology of events, that led to the complete degradation of the river's health and the ecosystem of that area of the Bormida Valley over the decades, will be presented. Additionally, studies conducted by regional, national and private agencies over the years, along with their respective results, pollutants identified, pollution levels, and the consequences of ACNA's activities on the soil, groundwater, the Bormida River, and the residents in the industrial area's vicinity, will be presented.

Finally, the Remediation Technologies and all the activities carried out by ENIRewind for the remediation and environmental restoration of the Cengio and Saliceto SIN, which have been ongoing for approximately 20 years, as well as the achieved objectives, will be described.

In conclusion, this thesis will demonstrate, through the presentation of the case study, how industrial activities carried out without adequate control and environmental compatibility criteria can deteriorate the health of an ecosystem and how challenging it is, from a regulatory, legislative, social, technological, time-consuming, and monetary perspective, to restore the state of a destroyed ecosystem.

This conclusion, when connected to the initial and central part of the thesis, will underline the propositions of the IPCC reports on the importance of safeguarding ecosystems in facing climate change. In fact, it will make understand how, considering the cumulative effect of anthropogenic pressures and environmentally incompatible activities scattered worldwide, some of which are significantly larger in scale compared to the case study (which represents only a localized event in a microregion of a relatively small European Nation), this can lead to the complete disintegration of ecosystems' functions as regulators of normal climate equilibrium.

Additionally, it will result in the loss of natural resilience to the already confirmed, certified, imminent, and present impacts of climate change. Ultimately, it will require substantial global economic expenditure for the remediation of damaged ecosystems (where possible) and will exact an economic and human cost in terms of lives, health, and well-being due to the absence or degraded state of these ecosystems.

1. Introduction

This thesis will, firstly, describe the main concepts and characteristics related to Climate Change, and possible solution strategies and technologies, focusing on the role of ecosystems as main natural barrier against the consequences of climate change. Their crucial importance, as stated by International Panel on Climate Change (IPCC) reports, is due to their ability to mitigate both the causes and the impacts of climate changes and consolidate a strong natural resilience for human society adaptation. So, safeguarding them from non-environmentally compatible human activities or restore them in case of environmental damage is fundamental.

In this context, to introduce the reader to the case study of this thesis (the environmental damage of Cengio and Saliceto Site of National Interest (SIN)), at the end of the fourth chapter there will be a description of the guidelines for the maintenance, control, and restoration of river ecosystems, along with the theoretical framework related to environmental damage, including analysis and evaluation criteria, methodologies, and strategies.

The case study will be described and analysed in detail, starting from the geographical and environmental characterization of the site, also involving a description of the ecosystem. Then the chronology of the events will be presented to describe the causes and circumstances that led to one of Italy's most significant environmental disasters, as well as analyse the components characterizing the impacts of industrial activities and pollution on the ecosystem, soil, the Bormida River, and the health of the residents in the surrounding areas of Cengio and Saliceto.

Finally, there will be a presentation of all the remediation technologies and activities carried out by ENIRewind, which have been ongoing for approximately 20 years, to restore and remediate to the catastrophic environmental damage occurred on this site.

Certainly, the role of this case study is crucial from a scientific, social, and historical point of view, in fact, the case of ACNA in Cengio has become an historic case regarding the detrimental consequences and negative impact on ecosystems that arise when industrial activities proceed without environmental compatibility standards, without proper regulations, controls, and management by the government and competent authorities.

The pollution and the repercussions of over a century of uncontrolled and environmentally incompatible industrial activities have affected an entire community, local economic activities, agricultural activities, their social structure, and the environmental and landscape heritage of an entire valley and its river.

Therefore, the purpose of this thesis will be the demonstration, by the description and analysis of the case study, of the crucial importance of preserving the health of ecosystems from industrial, and in general non-environmentally compatible human activities, and the necessity to remediate and restore them in case of environmental damage, along with all activities and technologies needed to achieve this fundamental objective.

2. Climate Change overview

Climate change is for sure the most important and urgent global challenge of the century; it is an imminent and pressing global issue that poses significant threats to the environment, human societies, and the world economy. It refers to long-term shifts and alterations in temperature patterns and weather patterns and environmental conditions, resulting from human activities that change the Earth's natural equilibrium.

In this chapter the main aspects that characterize the climate change will be presented, starting from a brief description of the climate system, then the understanding of the driving forces and the causes of the problem, finally an overview of the present and possible future consequences.

2.1 The climate system

The climate system refers to the interactions and processes that govern the Earth's climate. It is driven by energy from the Sun. Solar radiation reaches the Earth's surface and it is either absorbed or reflected back into space. The distribution of this energy is not uniform, leading to variations in temperature, atmospheric pressure, and wind patterns regulated by the exchange of energy, moisture, heat and momentum between the atmosphere, oceans, land surfaces, ice, and living organisms. Additionally, the Earth's rotation, the tilt of its axis, and the distribution of continents and oceans play significant roles in shaping the climate system. Understanding the climate system is essential for comprehending climate patterns, variability, and long-term changes, in fact it operates on different scales, ranging from local weather phenomena to global climate patterns, and different time scales, from short-term fluctuations such as El Niño and La Niña to long-term changes like ice ages and interglacial periods. The climate system is complex and influenced by various factors, including natural processes and human activities. The key components of the climate system are [1]:

1. Atmosphere: The thin layer of gases surrounding the Earth, including nitrogen, oxygen, carbon dioxide, and water vapor. It plays a crucial role in regulating temperature, redistributing heat, and transporting moisture through atmospheric circulation patterns. Greenhouse gases, such as carbon dioxide and methane, trap heat in the atmosphere, leading to the greenhouse effect and influencing climate.
2. Hydrosphere: This component consists of all the water on Earth, including oceans, lakes, rivers, groundwater, and atmospheric water vapor. The movement and distribution of water through the hydrological cycle have a significant impact on the climate system.
3. Cryosphere: The cryosphere encompasses frozen components of the Earth, including ice caps, glaciers, snow cover, permafrost, and sea ice. It plays a significant role in the Earth's energy balance by reflecting sunlight back into space. The melting of ice and the reduction of snow cover affect the planet's energy budget and can contribute to sea-level rise.
4. Lithosphere: The solid outer shell of the Earth, comprising the Earth's crust and uppermost mantle. The lithosphere interacts with the other components of the climate system through processes like weathering, volcanic activity, and the storage/release of greenhouse gases.

5. Land Surfaces: Land surfaces, including forests, grasslands, deserts, and urban areas, interact with the atmosphere and influence climate. Vegetation acts as a carbon sink, absorbing CO_2 from the atmosphere through photosynthesis. Land-use changes, such as deforestation and urbanization, can alter surface properties, leading to changes in temperature, moisture, and local climate.
6. Biosphere: The biosphere refers to all living organisms on Earth, including plants, animals, and microorganisms. The biosphere interacts with the atmosphere, water, and land surfaces through processes like photosynthesis, respiration, and the carbon cycle. Changes in climate can impact ecosystems, biodiversity, and species distribution.

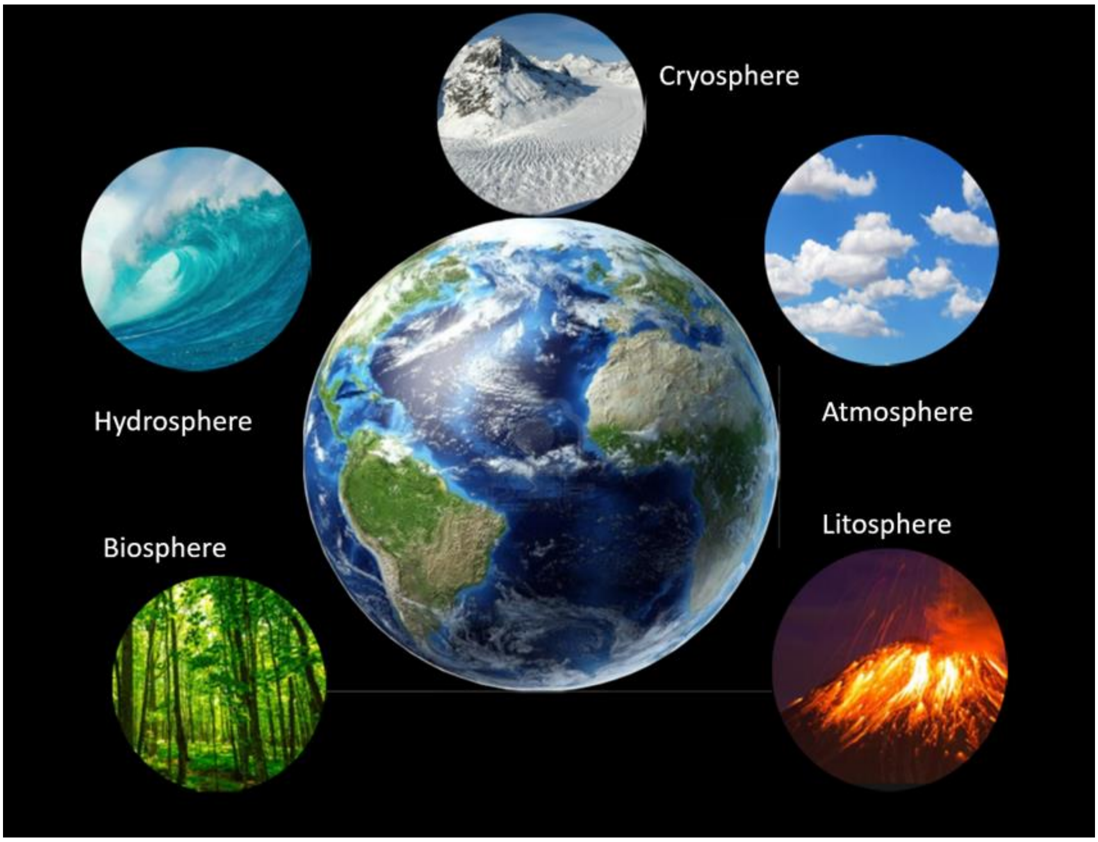


Figure 1. Climate system's components

Moreover, the other main aspects, processes and dynamics that characterize the climate system are [1]:

1. Radiative Forcing: Radiative forcing refers to the energy imbalance in the Earth's climate system caused by changes in the concentration of greenhouse gases and other factors. It measures the perturbation of the planet's energy balance, and it is quantified in watts per square meter. Positive radiative forcing leads to a warming effect, while negative forcing causes cooling.

2. Ocean Circulation: The oceans play a fundamental role in redistributing heat globally through thermohaline circulation. The movement of warm and cold ocean currents affects regional climates and influences the exchange of heat and moisture with the atmosphere. Changes in ocean circulation patterns can have significant impacts on climate variability, including phenomena like El Niño and La Niña, which occur in the tropical Pacific Ocean.

3. Feedback Mechanisms: Feedback mechanisms in the climate system can either amplify (positive feedback) or dampen (negative feedback) the initial climate change. For example, the ice-albedo feedback is a positive feedback mechanism where melting ice reduces surface reflectivity, causing more sunlight to be absorbed and further warming the climate. On the other hand, the carbon cycle acts as negative feedback, increasing atmospheric CO_2 stimulates plant growth, which can absorb some of the excess carbon and mitigate the rise in CO_2 levels.
4. Climate Sensitivity: Climate sensitivity refers to the amount of warming expected in response to a doubling of atmospheric CO_2 concentrations. It is a measure of the climate system's response to external forcing. Estimating climate sensitivity is complex, as it involves understanding the interactions between different components of the climate system. Current estimates suggest a likely range of climate sensitivity between 1.5°C and 4.5°C, with higher values associated with more significant climate impacts.
5. Paleoclimate Studies: Paleoclimate studies provide valuable insights into past climate conditions and help us understand the behaviour of the climate system under different conditions. By analysing ice cores, tree rings, and sediment records, scientists reconstruct past climate patterns and investigate natural climate variability. This historical context allows us to better understand the current and future climate changes resulting from human activities.
6. Earth System Models: Earth System Models (ESMs) are complex computer models that simulate the interactions between different components of the climate system. They incorporate physical, chemical, and biological processes to simulate the past, present, and future climate. ESMs help researchers project future climate scenarios, assess the impacts of different greenhouse gas emission scenarios, and inform policy decisions.

Understanding the climate system involves studying the interactions and processes within and between these components. Scientists study the climate system through a combination of data observations, computer modelling, climate models, and analysis of past climate records preserved in natural archives, to simulate and understand the behaviour of the climate system. The study of the climate system is crucial for predicting future climate conditions, assessing the impacts of climate change, and formulating effective strategies for mitigation and adaptation.

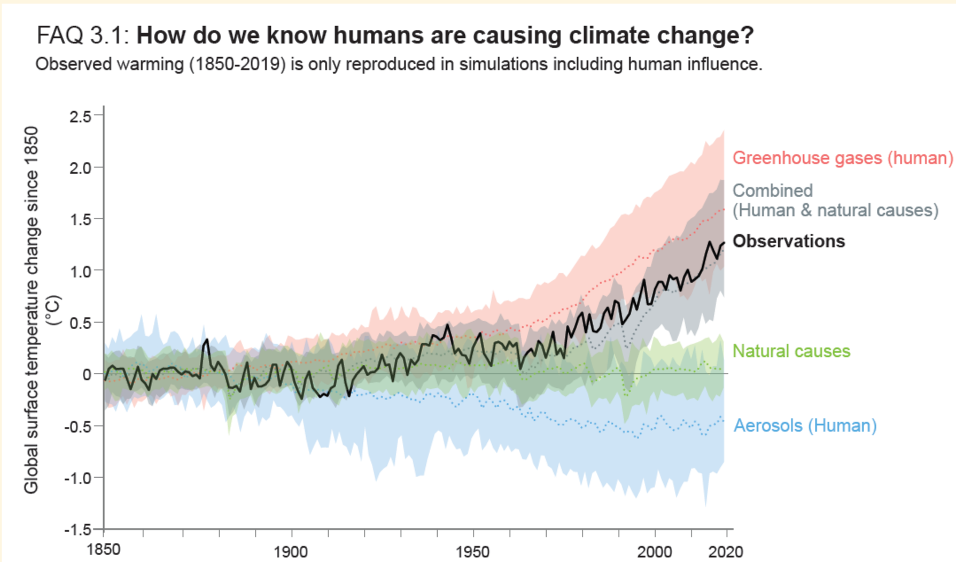
2.2 Causes and driving forces of Climate Change

Over the past century, there has been overwhelming scientific consensus that climate change is primarily driven by human activities, particularly the release of greenhouse gases into the atmosphere. The increase in atmospheric carbon dioxide (CO_2) concentration is extensively supported by observational data and scientific studies.

Numerous references provide robust evidence of human-induced climate change, including the Intergovernmental Panel on Climate Change (IPCC) reports, which summarize the findings of thousands of scientists worldwide. The IPCC's Fifth Assessment Report (AR5) in 2014 and the more recent Sixth Assessment Report (AR6) in 2021-2023 highlight the significant role of human activities in causing climate change. These reports emphasize that the observed increase in global average surface temperature since the mid-20th century is unprecedented in the past millennium and is directly attributed to human-induced greenhouse gas emissions. [2][3]

Studies have shown that the rise in CO_2 concentration is largely attributable to the burning of fossil fuels such as coal, oil, and natural gas, as well as deforestation and land-use changes. The release of CO_2 and other greenhouse gases traps heat in the atmosphere, leading to the greenhouse effect and subsequent warming of the planet. Historical records of CO_2 concentrations, derived from ice cores and other sources, clearly demonstrate that current levels are well above natural fluctuations and have risen sharply since the Industrial Revolution. [4]

Observational evidence further supports the anthropogenic nature of climate change. Scientists have documented changes in temperature, precipitation patterns, sea level rise, and the melting of ice caps and glaciers, which are all consistent with the expected impacts of human-induced global warming. Sophisticated climate models, incorporating various factors such as greenhouse gas emissions, solar radiation, volcanic activity, and aerosols, have successfully reproduced past climate conditions and projected future climate scenarios.



FAQ 3.1, Figure 1 | Observed warming (1850–2019) is only reproduced in simulations including human influence. Global surface temperature changes in observations, compared to climate model simulations of the response to all human and natural forcings (grey band), greenhouse gases only (red band), aerosols and other human drivers only (blue band) and natural forcings only (green band). Solid coloured lines show the multi-model mean, and coloured bands show the 5–95% range of individual simulations.

Figure 2. Prove of human driven climate change

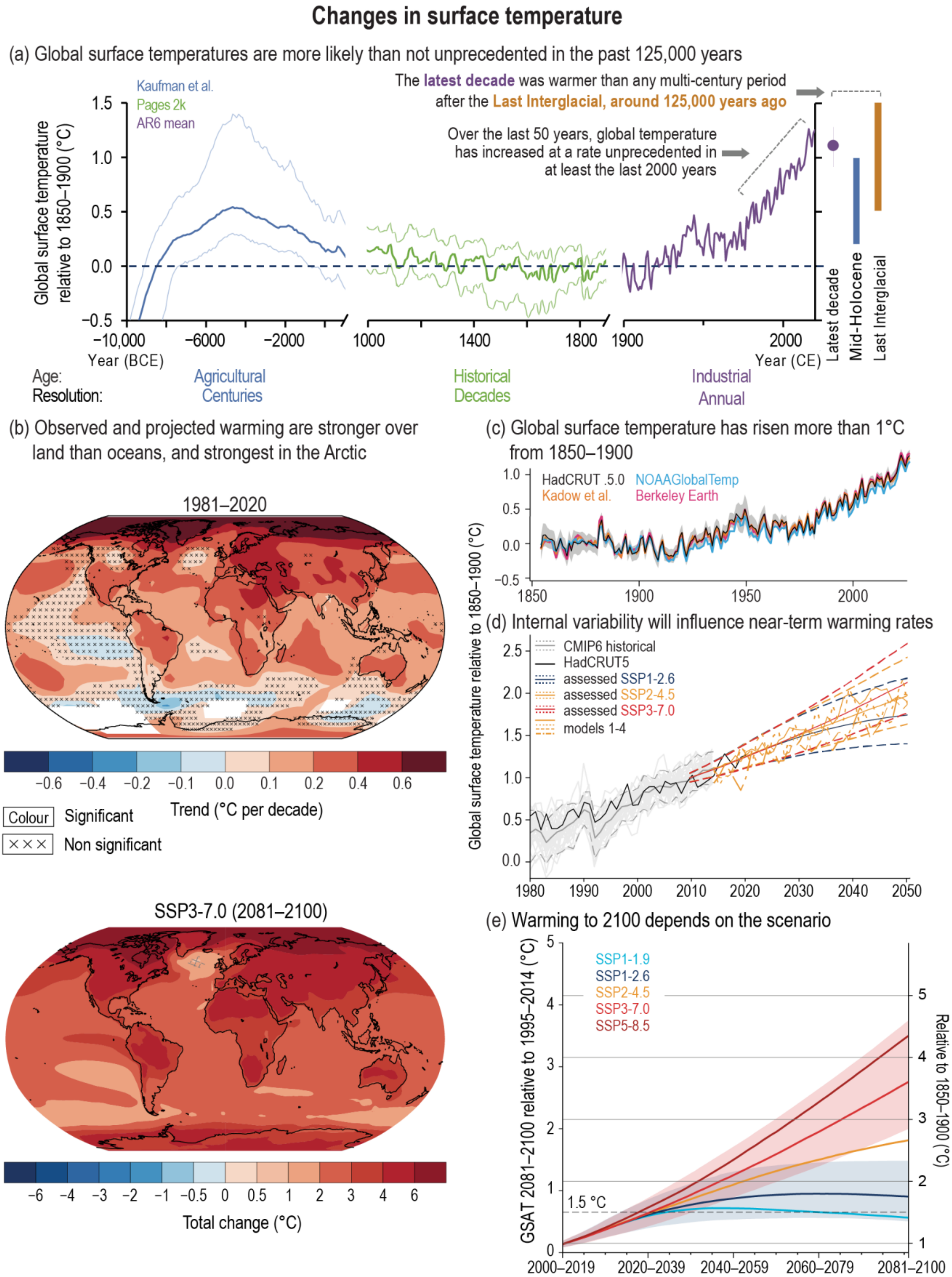


Figure 3. Changes in surface temperature

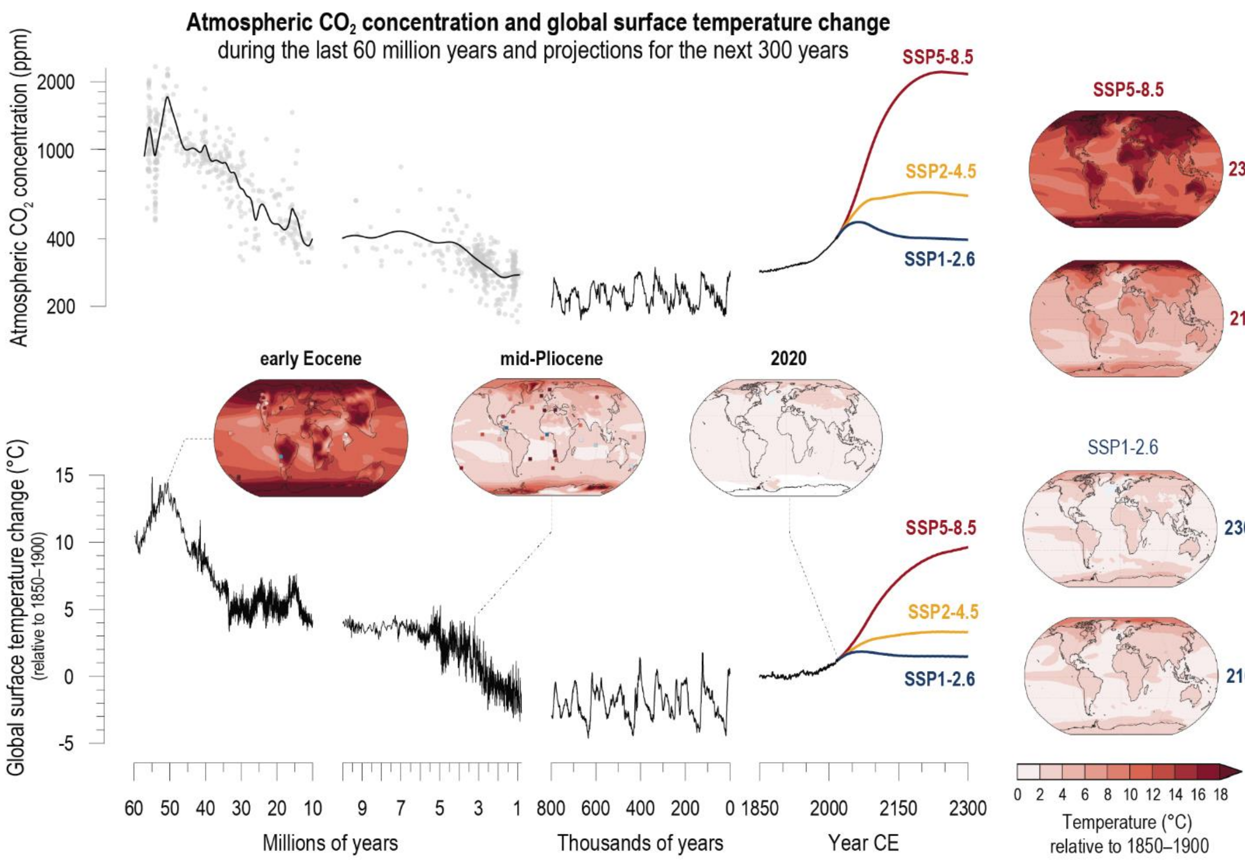


Figure 4. Atmospheric CO_2 concentration and global surface temperature change

The above three figures are taken from the IPCC's AR6 and show the changes in global average surface temperature and atmospheric CO_2 in time scale from millions, thousands to tens of year.

The IPCC is a leading international body responsible for evaluating and synthesizing scientific research on climate change. Their comprehensive assessments provide critical insights into the causes, impacts, and potential solutions to address this global challenge. In fact, the IPCC's assessments provide robust evidence on the causes, impacts, and necessary actions to address climate change. With human activities driving global warming and its severe consequences, it is crucial to prioritize mitigation efforts to reduce GHG emissions and transition to sustainable practices. Simultaneously, adaptation measures must be implemented to protect vulnerable communities and ecosystems from the impacts of climate change. By heeding the IPCC's findings, policymakers, scientists, and individuals can work together to safeguard the planet's future and create a sustainable and resilient world.

The key findings and assessments from a selection of the main important reports are presented:

1. IPCC Special Report on Global Warming of 1.5°C (SR15): This report, published in 2018, assesses the impacts of global warming of 1.5°C above pre-industrial levels and the potential pathways to limit temperature increase to this threshold. It highlights that even a half-degree increase beyond this level could have significant consequences for ecosystems and human well-being. The report stresses the urgency of reducing greenhouse gas emissions to limit the severity of climate change impacts. [6]

2. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC): Released in 2019, this report focuses on the impacts of climate change on the world's oceans and cryosphere (frozen parts of the planet). It highlights how increasing temperatures are causing marine heatwaves, sea-level rise, and disruptions to marine ecosystems. The report also addresses the implications for coastal communities, biodiversity, and global food security. It underscores the need for both mitigation and adaptation measures to safeguard these vulnerable systems. [7]

3. IPCC Special Report on Climate Change and Land (SRCCL): Published in 2019, this report assesses the interlinkages between climate change, land use, and sustainable land management practices. It emphasizes that land plays a crucial role in the climate system and is affected by climate change impacts such as desertification, deforestation, and soil degradation. The report discusses the potential of sustainable land management practices to mitigate climate change and enhance food security. [8]

4. IPCC Sixth Assessment Report (AR6): The AR6, published in 2021-2023, provides the most up-to-date understanding of climate change. It presents a comprehensive synthesis of scientific knowledge on the physical science basis of climate change, impacts, and future risks. It highlights that human activities are unequivocally causing global warming, leading to unprecedented changes in the Earth's climate system. The report emphasizes the urgency of reducing greenhouse gas emissions to limit global warming to well below 2 degrees Celsius above pre-industrial levels and striving for 1.5 degrees Celsius. It also addresses key sectors and regions, highlighting the need for adaptation and mitigation measures and outlining potential pathways and strategies for achieving these goals. [2]

These reports serve as critical references for policymakers, scientists, and stakeholders, providing detailed analyses and evidence-based assessments of climate change and its impacts. They offer comprehensive reviews of scientific literature, modelling scenarios, and expert inputs to guide decision-making and actions toward mitigating and adapting to climate change.

The IPCC identifies human activities, primarily the burning of fossil fuels and deforestation, as the main drivers of climate change. The burning of fossil fuels releases carbon dioxide (CO_2) and other greenhouse gases (GHGs) into the atmosphere, leading to the greenhouse effect and resulting in global warming. On the other hand, deforestation reduces the Earth's capacity to absorb CO_2 and contributes to additional emissions, exacerbating climate change.

Moreover, going deeper in the description of the causes of Climate Change outlined by IPCC, here a list of driving forces and sectors is presented:

- Greenhouse Gas Emissions: The increase in GHGs, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), traps heat in the Earth's atmosphere, leading to global warming. For instance, the burning of fossil fuels for electricity generation, transportation, and manufacturing activities releases substantial amounts of CO_2. Methane emissions arise from agricultural practices, landfills, and fossil fuel production. Nitrous oxide is mainly emitted from agricultural and industrial activities.

- Pollution and Aerosols: Pollution from industrial processes and transportation degrades air and environmental quality. Pollutants and contaminants are dispersed on land, ground, surface water, groundwater, sea, or oceans, altering the natural quality and health of the planet. Air pollutant as particulate matter and aerosols can either cool or warm the atmosphere, depending on their composition. Sulphate aerosols from burning fossil fuels have a cooling effect, whereas black carbon aerosols from incomplete combustion contribute to warming. The complex interactions between aerosols and climate further complicate the understanding of climate change dynamics.
- Deforestation: The loss of forests and conversion of land for agriculture or urbanization significantly impact climate change. Deforestation reduces the Earth's capacity to absorb CO_2 through photosynthesis, thereby intensifying the greenhouse effect. The removal of forests also disrupts ecosystems and reduces biodiversity, further exacerbating the vulnerability of ecosystems and communities to climate change.
- Agriculture and Land Use: The agriculture sector contributes to climate change through various processes. Livestock farming, particularly cattle, produces methane as a by-product of enteric fermentation in the digestive systems of animals. Intensive agricultural practices, such as large-scale monoculture farming and the use of synthetic fertilizers, also contribute to climate change. Manure management and the decomposition of organic waste in landfills also release methane. Agricultural practices such as rice cultivation and the use of synthetic fertilizers lead to the release of nitrous oxide (N_2O), a potent greenhouse gas. Land-use changes such as deforestation, urbanization, and conversion of natural landscapes for agriculture, as expanding crop production and grazing areas, and infrastructure contribute to climate change in the loss of carbon sinks, releasing stored carbon dioxide into the atmosphere. Land-use changes can also impact regional climate patterns by altering the balance of evaporation and precipitation.
- Waste Generation and Management: Improper waste management, including inadequate recycling and organic waste decomposition in landfills, contributes to greenhouse gas emissions. Landfills release significant amounts of methane (CH_4), which has a higher warming potential than carbon dioxide (CO_2). Implementing effective waste management strategies such as recycling, composting, and methane capture can help reduce these emissions.
- Urbanization and Infrastructure: Rapid urbanization leads to increased energy consumption, transportation needs, and demand for resources, which contribute to greenhouse gas emissions. The construction of buildings and infrastructure, particularly those that rely on energy-intensive materials and processes, generates substantial emissions. Urban development can also contribute to the loss of green spaces, leading to reduced carbon sequestration and increased urban heat island effects.
- Fugitive Emissions: Fugitive emissions refer to the unintentional release of greenhouse gases during extraction, production, transportation, and storage of fossil fuels. Methane (CH_4) leakage during oil

and gas extraction and distribution processes is a notable source of fugitive emissions. Methane is a potent greenhouse gas, and addressing these leaks is crucial for mitigating climate change.

- Industrial Sector: The industrial sector encompasses manufacturing, construction, and industrial processes such as cement production and chemical manufacturing. Industrial sector contributes to climate change primarily through the combustion of fossil fuels for energy and the release of greenhouse gases during industrial processes. Industries emit carbon dioxide (CO_2) through the burning of fossil fuels for electricity generation and heat production. They also release methane (CH_4) during certain industrial processes, such as oil and gas extraction, coal mining, and waste management. Industrial activities also generate nitrous oxide (N_2O) emissions from chemical reactions and the use of nitrogen-based fertilizers. Additionally, industrial processes like cement production release large amounts of CO_2 as a by-product. Overall, the industrial sector is a significant contributor to greenhouse gas emissions, particularly in developed countries with extensive manufacturing and heavy industries.
- Energy Sector: The energy sector includes the production, conversion, and consumption of energy from fossil fuels (coal, oil, and natural gas), as well as renewable energy sources. The energy sector is the largest contributor to global greenhouse gas emissions. The burning of fossil fuels for electricity generation, heating, and cooling releases substantial amounts of CO_2 into the atmosphere. Power plants that rely on coal as a fuel source are particularly carbon intensive. The extraction and processing of fossil fuels, such as oil and natural gas, also result in the release of methane. Furthermore, the energy sector contributes to climate change through the release of other pollutants, such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulate matter (PM).
- Transportation Sector: The transportation sector is a significant contributor to greenhouse gas emissions, primarily through the combustion of fossil fuels in vehicles. The burning of gasoline and diesel fuels in cars, trucks, motorcycles, and airplanes releases CO_2, contributing to climate change. In addition to CO_2 emissions, transportation also generates pollutants like nitrogen oxides (NO_x) and particulate matter (PM), which have adverse effects on air quality and human health.

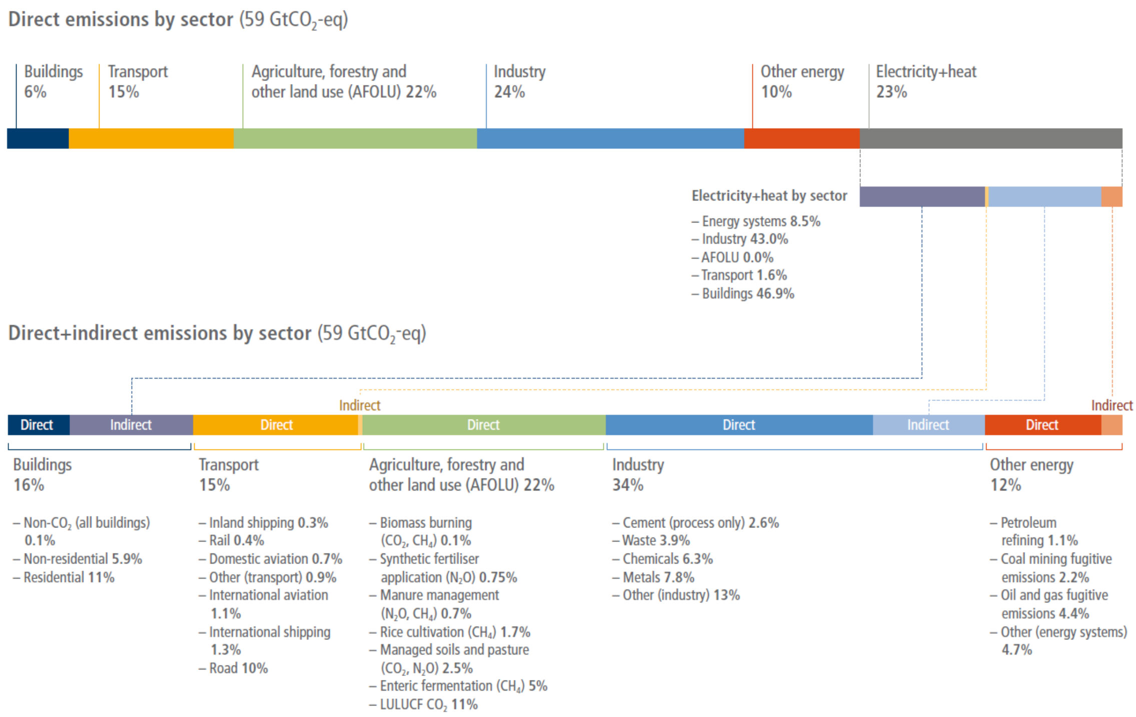


Figure 5. Emissions by sector

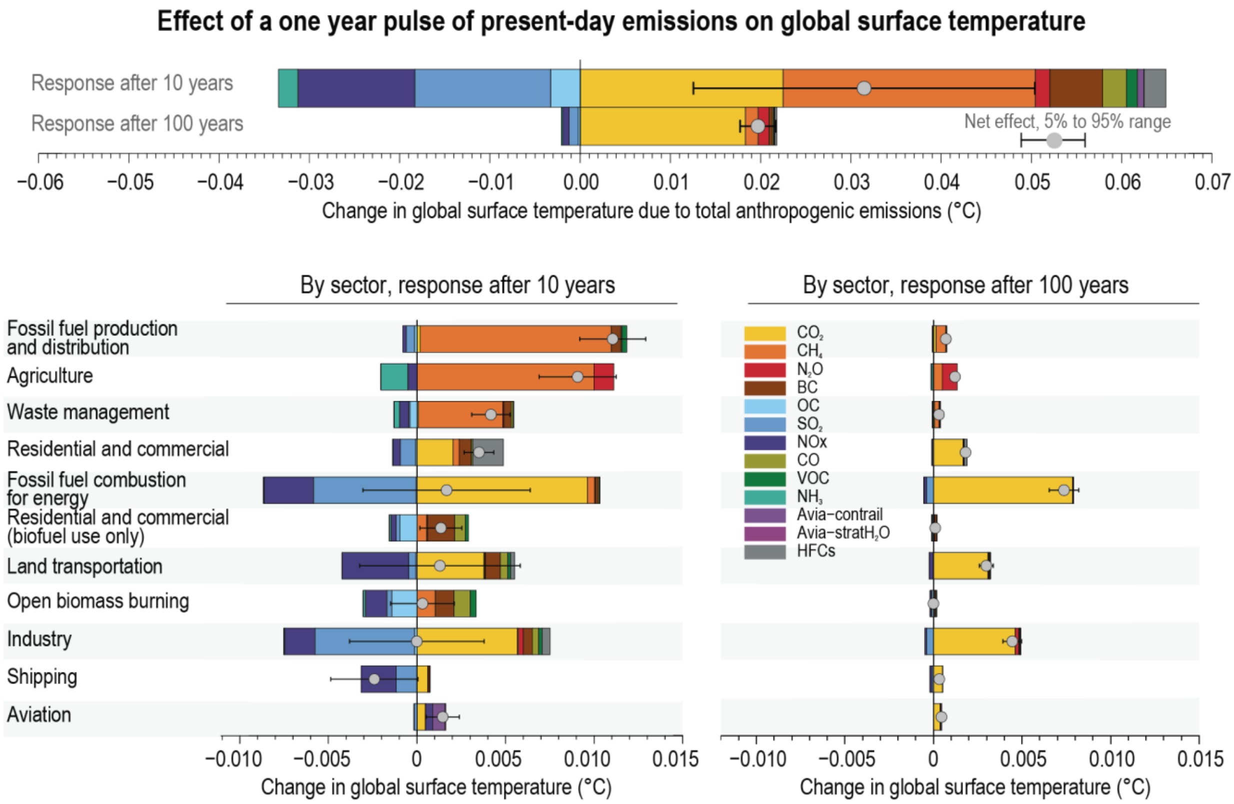


Figure 6. Effect of emissions on global surface temperature

These causes and driving forces of climate change are interconnected and often reinforce each other. Moreover, it is important to note that the contributions of these sectors vary among countries. Developed nations (USA, EU, Russia), historically having higher emissions, often have a larger share in global emissions compared to developing nations. However, developing countries with rapidly industrializing economies have seen substantial increases in their emissions in recent years (Brazil, India, China which is now the world's largest emitter of carbon dioxide and heavily relies on coal for energy production). [9]

Efforts are being made at both national and international levels to address climate change and transition to a more sustainable future, led by The Conference of the Parties (COP) which is an annual meeting organized under the United Nations Framework Convention on Climate Change (UNFCCC). The COP brings together representatives from countries worldwide to discuss and negotiate climate-related issues. The COP meetings aim to assess progress in dealing with climate change, set targets and commitments, and facilitate international cooperation.

The COP meetings have resulted in important agreements and milestones, such as:

1. Kyoto Protocol: Adopted in 1997, the Kyoto Protocol established binding emission reduction targets for developed countries for the period 2008-2012. It also introduced mechanisms for emissions trading and clean development project.

2. Paris Agreement: The Paris Agreement, adopted in 2015, aims to limit global warming well below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit it to 1.5 degrees Celsius. It includes commitments from both developed and developing countries to reduce greenhouse gas emissions, enhance adaptation efforts, and provide financial support to developing nations for climate action.

The goals of the COP meetings evolve over time, focusing on reviewing progress, strengthening commitments, and promoting global climate action. They serve as pivotal platforms for international collaboration and decision-making on climate change.

2.3 Impacts and consequences of Climate Change

Climate change has far-reaching impacts and consequences that affect various aspects of the environment, society, and the economy. More than the anthropogenic sphere, these impacts affect also and mostly ecosystems, biodiversity, and the delicate balance of life on Earth.

Climate change and its consequences have the potential to be catastrophic, irreparable, and disruptive for living beings, the Earth's systems, the climate system, and our way of life. The magnitude and complexity of the challenges cannot be overstated. The scientific consensus overwhelmingly points to human activities as the primary driver of climate change, particularly through the emission of greenhouse gases.

First, the main impact of climate change is the average global temperatures rising (as seen in the last paragraph and figures). Global warming results from the accumulation of greenhouse gases in the atmosphere, primarily carbon dioxide from human activities. The increased concentration of these gases leads to the greenhouse effect, trapping heat and causing a rise in average temperatures. This temperature increase affects various aspects of the Earth's system, for example the melting of ice caps and glaciers alters oceanic salinity and circulation, and sea-level rise. This poses a significant threat to coastal areas, leading to increased coastal erosion, flooding, saltwater intrusion into freshwater sources. The temperature rise alters also soil moisture, humidity, precipitation, and other weather patterns, and obviously lead to shifts in ecosystems. [12]

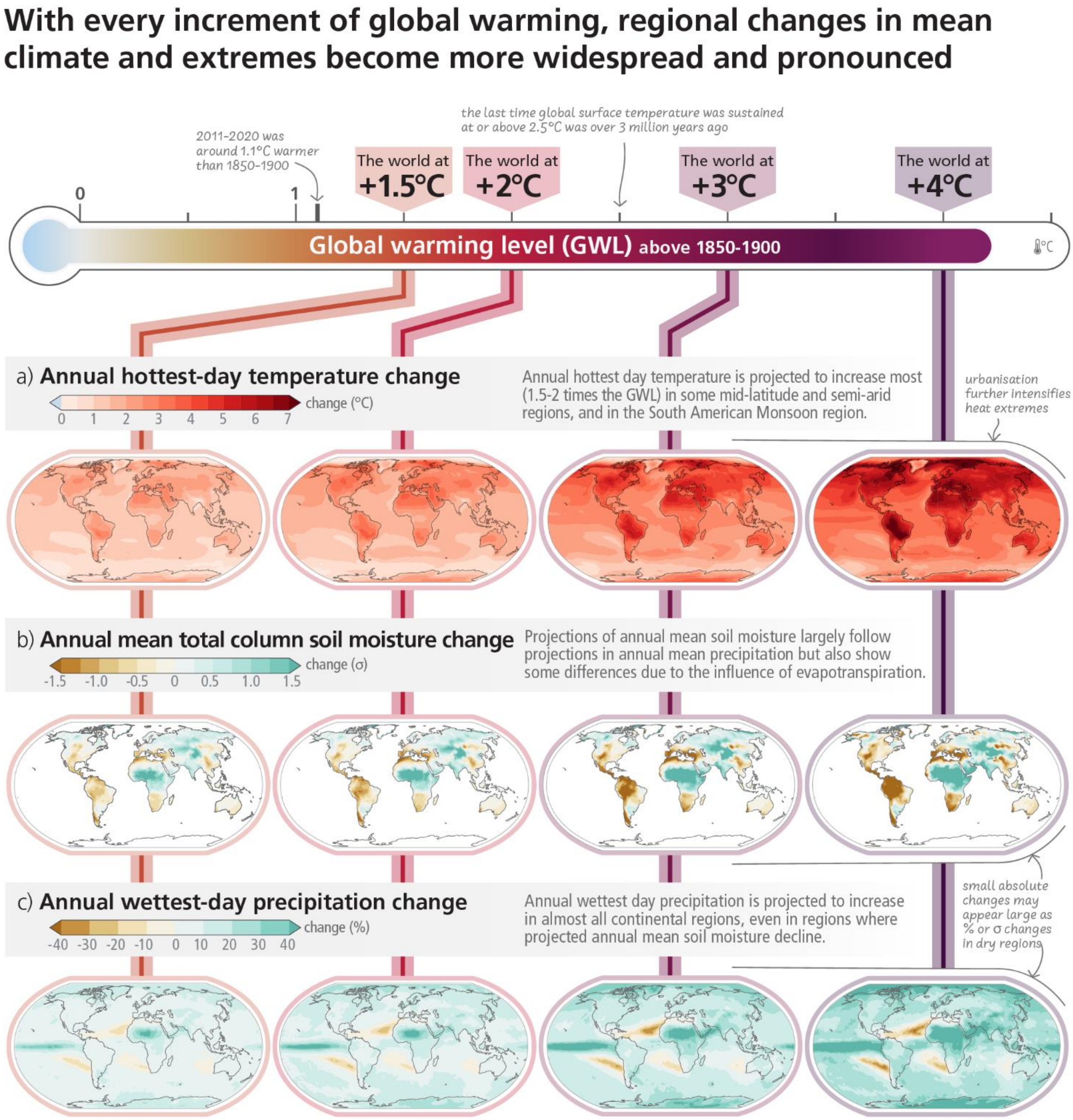


Figure 7. Global warming and climate changes

Completely interconnected with rising temperatures, and so the imbalance of thermal energy and energy vectors in the climate system, there are more cascading consequences such as extreme weather events. So, climate change intensifies the frequency and severity of extreme weather events, including hurricanes, cyclones, droughts, floods, and storms. These events have devastating impacts on environment and communities, causing loss of habitats and ecosystems, loss of lives, displacements, property damages, and disruptions to infrastructure, agriculture, and economies.

As already said, the impacts of climate change disrupt ecosystems and biodiversity. Changes in temperature, rainfall patterns, and habitats can lead to the loss of species, reduced biodiversity, and ecosystem degradation. This affects ecosystem services, such as pollination, water purification, and carbon sequestration, which are essential for human well-being and the functioning of the planet. Moreover, there are ecosystem feedbacks, feedback mechanisms within ecosystems, amplifying the warming process. For example, the melting of permafrost releases methane, a potent greenhouse gas, further contributing to global warming. Understanding and monitoring these feedback loops is crucial for climate modelling and informing mitigation strategies. Engineering solutions include carbon capture and storage technologies, sustainable land management practices, and promoting the conservation and restoration of carbon-rich ecosystems such as forests and wetlands.

The repercussions of climate change extend far beyond environmental concerns, physical and ecological disruptions. They encompass every aspect of our lives, impacting our health, economies, food security, and social and political system. The resulting social tensions and conflicts further strain global stability and cooperation. The interconnectedness of these consequences creates a ripple effect, amplifying the overall impact and exacerbating existing vulnerabilities and inequalities. As regards health impacts, climate change poses direct and indirect risks to human health: heatwaves, exacerbated by global warming, increase the prevalence of heat-related illnesses and deaths. Poor air quality resulting from increased pollution and wildfires contributes to respiratory and cardiovascular diseases. Changes in precipitation patterns and temperature can affect the spread of waterborne and vector-borne diseases such as malaria and dengue fever. Engineering solutions involve developing climate-resilient healthcare infrastructure, improving urban planning to mitigate heat island effects, and promoting clean energy sources to reduce air pollution.

As regards climate change impact on global food production and water resources: changing precipitation patterns, increased droughts, and extreme weather events affect agricultural productivity, leading to crop failures, reduced yields, and food scarcity. These factors, combined with population growth, can exacerbate food and water scarcity, leading to increased competition and potential conflicts. Engineering interventions include improving irrigation systems, adopting climate-smart agricultural practices, enhancing water management techniques, and developing drought-resistant crop varieties. Additionally, sustainable water management and conservation strategies are vital for ensuring water availability in the face of changing climate conditions. [11]

As regards economic consequences of the climate change: extreme weather events, crop failures, and disruptions in supply chains can lead to reduced agricultural productivity, increased food prices, and economic losses in sectors such as tourism, fisheries, and infrastructure. The costs of adapting to climate change and recovering from climate-related disasters can put a strain on national budgets.

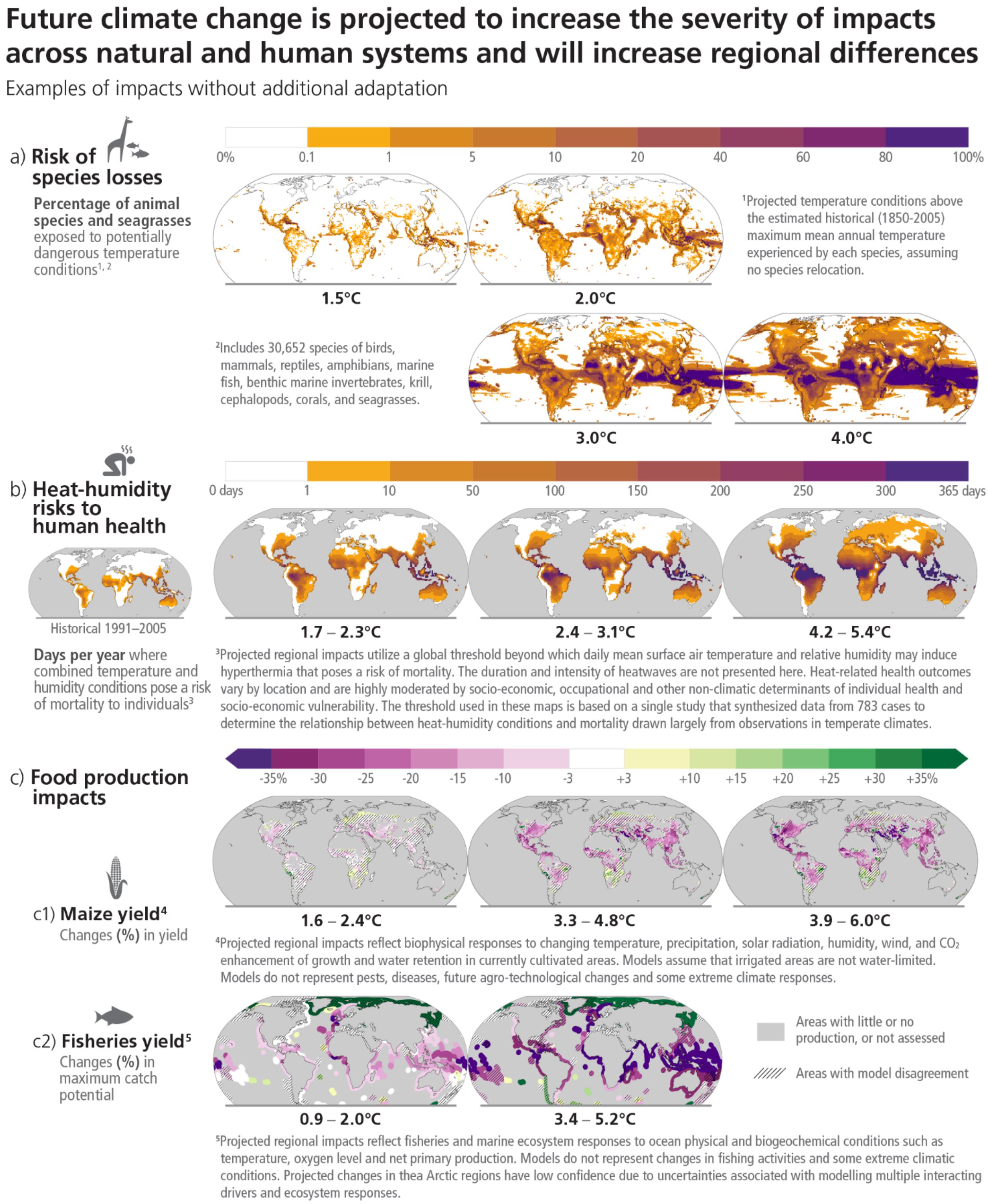


Figure 8. Impacts of future climate change projections

As regards climate change impacts on society and social consequences: climate change-induced events force people to migrate or become displaced, resulting in social, economic, and political challenges. Vulnerable communities, particularly those in low-income regions, bear the brunt of these disruptions, facing increased poverty, food and water insecurity, and displacement. Low-lying island nations and densely populated coastal regions, for example, are particularly vulnerable to the impacts of sea-level rise. Another aspect is the creation of new competition over scarce resources, such as water and land, that can lead to conflicts, political instability, and wars. Engineering approaches involve providing resilient housing for displaced populations, supporting sustainable urban planning, and integrating climate change considerations into migration and international policies. Collaborative efforts between countries are determinant to address the challenges associated with climate-induced migration and fostering international cooperation to address security risks. [12]

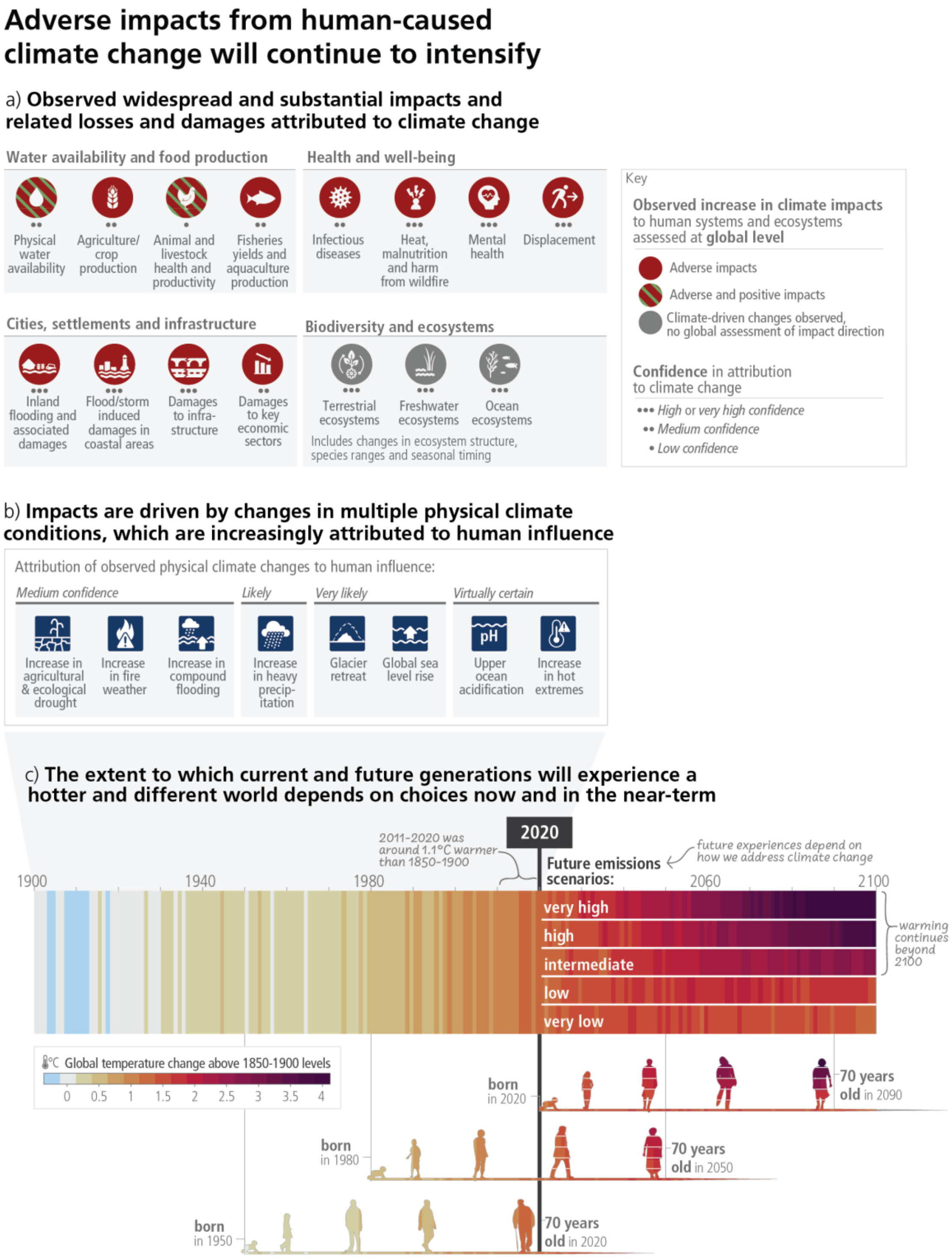


Figure 9. Adverse impacts from human-caused climate change

One of the most alarming aspects of climate change is the potential for irreversible damage. As approaching critical thresholds and tipping points, the Earth's systems may undergo abrupt and irreversible changes, such as the collapse of ice sheets or the release of large amounts of methane from permafrost. These events could trigger cascading effects, intensifying the severity and speed of climate change impacts, and leaving little room for mitigation or adaptation measures.

For these reasons, understanding the current situation, be capable of making predictions and to create reliable models describing future situation is fundamental to face in time and with the right mitigation and adaptation measures the climate change. To make future climate projections, the IPCC utilizes various climate models that are complex mathematical representations of the Earth's climate system, incorporating physical, chemical, and biological processes to simulate how the climate behaves. They are based on fundamental laws of physics and incorporate factors such as greenhouse gas emissions, atmospheric composition, solar radiation, and ocean currents, among others. Climate models are run on powerful supercomputers and generate simulations of the Earth's climate under different scenarios. These scenarios, often referred to as Representative Concentration Pathways (RCPs) in previous IPCC reports, have been updated to Shared Socioeconomic Pathways (SSPs) in the IPCC AR6. [14]

RCPs were used in previous IPCC reports, such as the IPCC AR5, to represent different greenhouse gas concentration trajectories. These pathways were developed by integrating information from climate models and socio-economic scenarios. RCPs are named according to the radiative forcing level (in Watts per square meter) that they would induce by the year 2100.

SSPs describe different potential futures of human society, including demographic, economic, and technological developments. They are not predictions or forecasts themselves but provide a range of possible pathways that represent different assumptions about future greenhouse gas emissions and socio-economic conditions. SSPs are intended to capture a broad spectrum of possible futures, allowing researchers to explore how different choices and circumstances might impact the climate system.

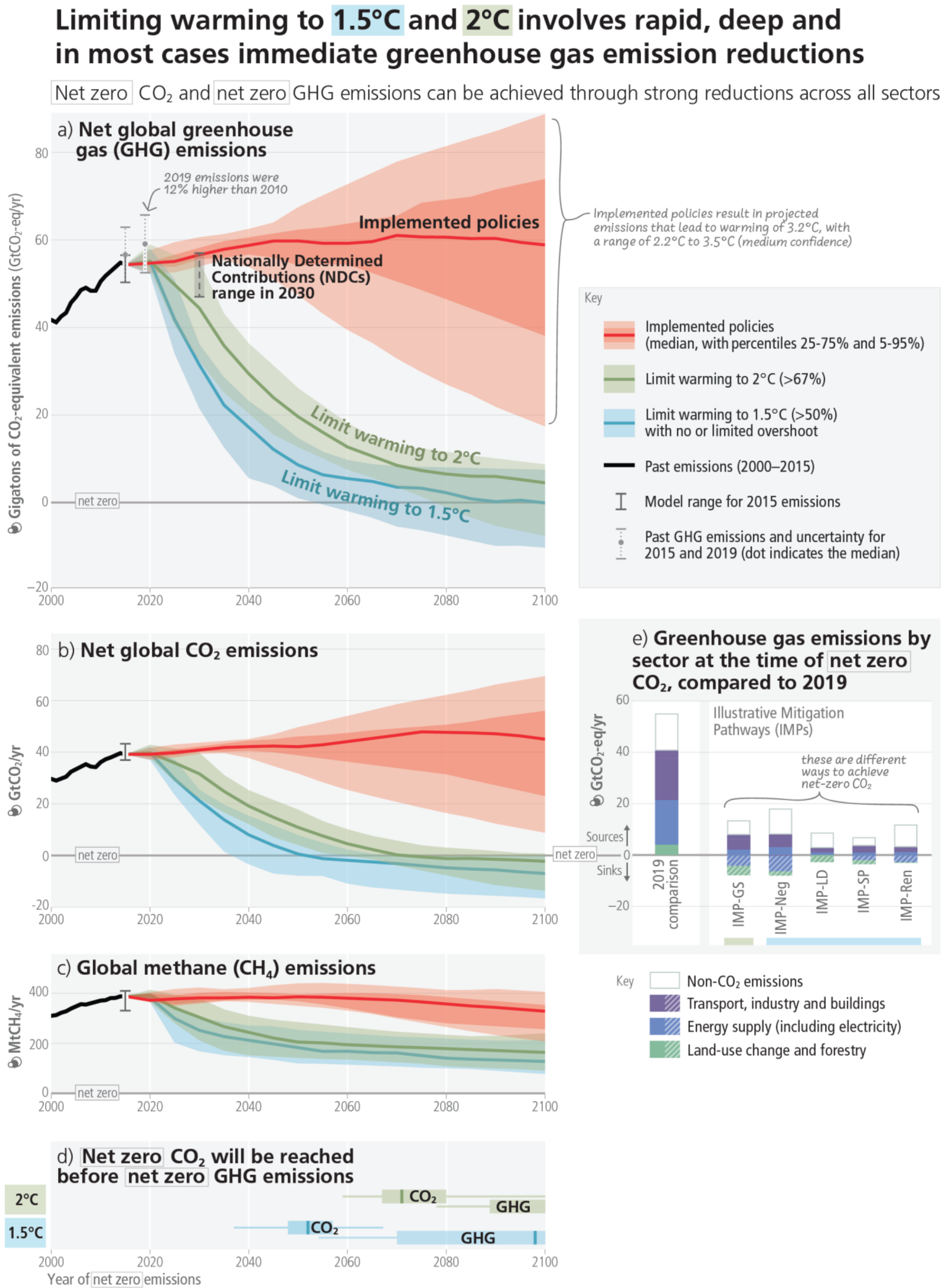


Figure 10. Emission scenarios

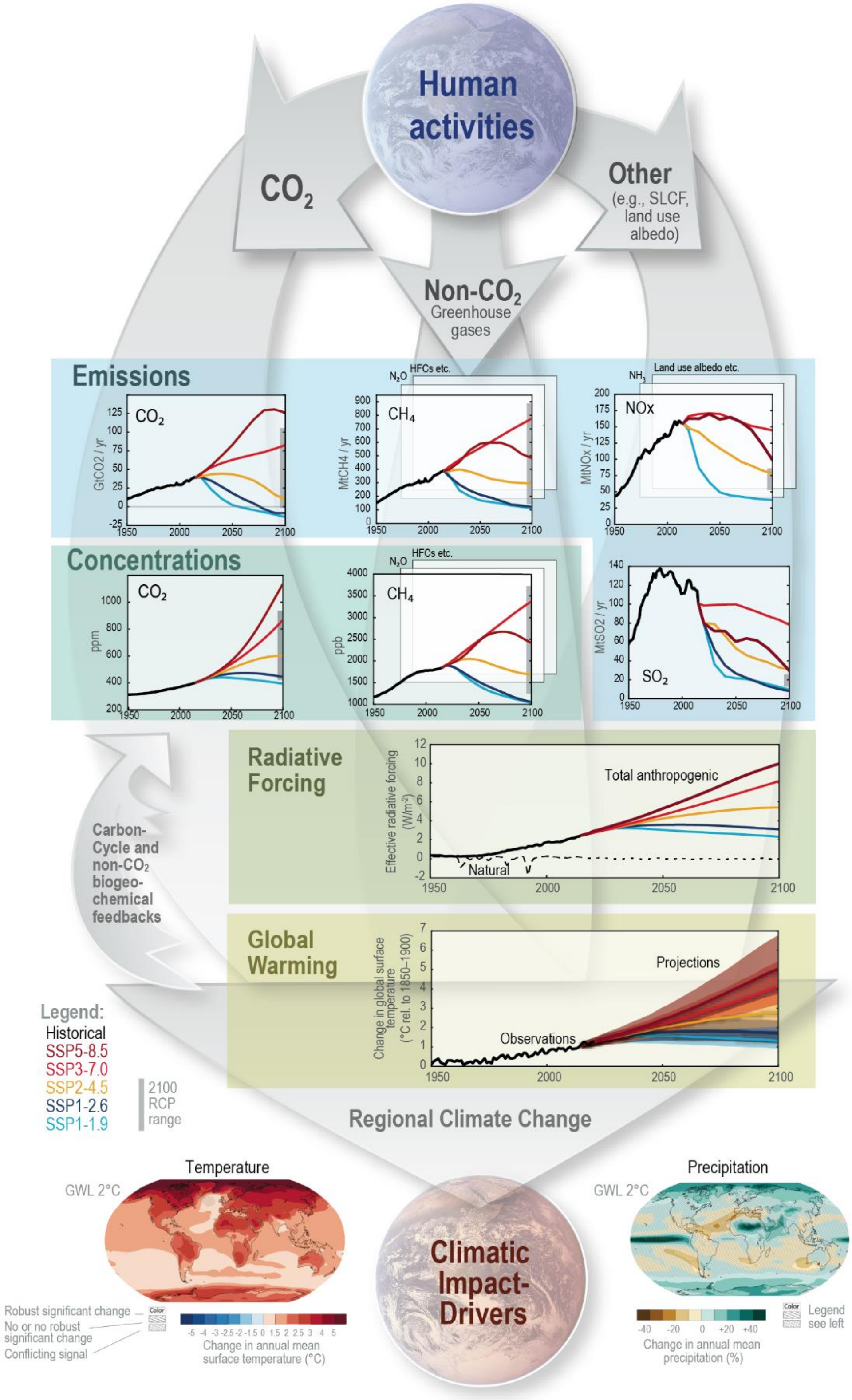
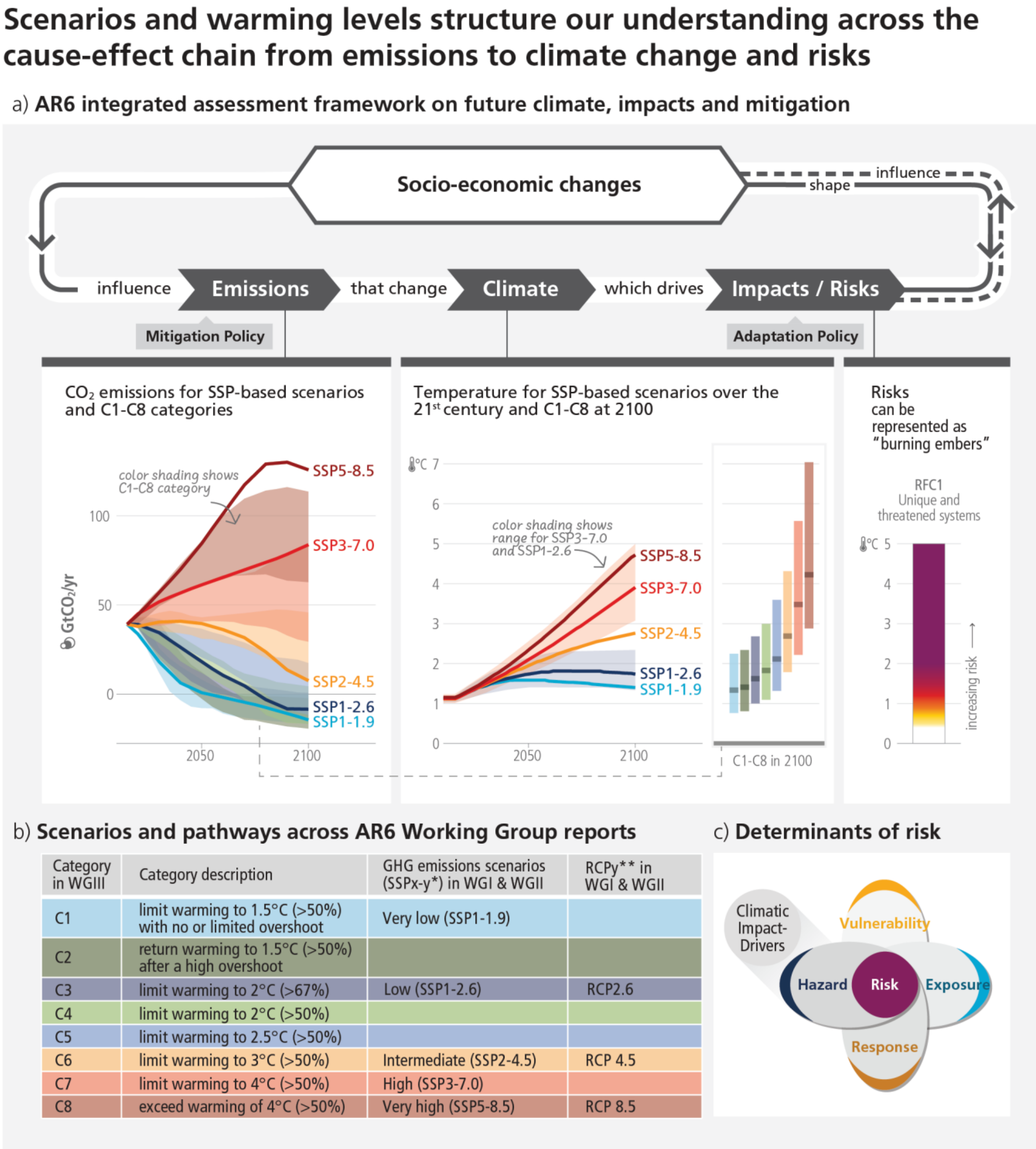


Figure 11. Human-caused climatic impact-drivers

The IPCC AR6 report includes five SSPs, ranging from SSP1 to SSP5, each with its own set of assumptions and corresponding emissions trajectories. SSP1 represents a sustainable future where socio-economic development is environmentally friendly, with strong climate policies, sustainable development goals, and increased equality. SSP2 represents a middle-of-the-road pathway where socio-economic development follows a conventional trajectory, with some improvements in sustainability but also challenges in achieving climate goals. SSP3 assumes a fragmented future with high regional inequality, slow economic growth, and limited environmental regulations, leading to higher greenhouse gas emissions. SSP4 explores a future with increased inequality, focused on fossil fuel development, and slower technological advancements, resulting in high energy demand and emissions. SSP5 represents a future where socio-economic development is characterized by high fossil fuel use, limited climate policies, and high energy demand, resulting in substantial greenhouse gas emissions. [14]



Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

Figure 12. Shared Socioeconomic Pathways (SSPs)

So, as seen until now, even if the challenges are immense, there is still hope for meaningful action. International agreements like the Paris Agreement and the efforts of scientists, corporations, organizations, governments, and public movements demonstrate a growing recognition of the urgency to address climate change. In the next chapter will be analysed the decisive steps, strategies, and technologies to mitigate the worst impacts of climate change.

In conclusion, the consequences of climate change are not merely abstract concepts but real and pressing challenges with far-reaching implications. Acknowledging the catastrophic potential, the disruptive nature, and the irreparable damage that can result from climate change is a call to action for citizens, governments, and nations all to take responsibility, make informed choices and laws, and a collective effort for a sustainable and resilient future.

3 Solutions, strategies, and technologies

As discussed in the last chapter the scientific community and the IPCC's assessments provide robust evidence of the anthropogenic forcing on the climate change, and so its causes, and its present and possible future impacts. On the other hand, the IPCC also outlined the necessary actions to address climate change. With human activities driving global warming and its severe consequences, it is consequential to prioritize mitigation efforts to reduce GHG emissions and transition to sustainable practices. Simultaneously, adaptation measures must be implemented to protect vulnerable communities and ecosystems from the impacts of climate change.

It is possible to say that mitigation strategies act on reducing or possibly eliminating the causes of climate change (GHGs emissions), while adaptation strategies act on the consequences, so try to reduce the impact of climate change on communities, environment, society, economy, production and consumption sectors.

Addressing the problems and consequences of climate change requires a multidisciplinary approach that combines scientific research, technological innovations, policy interventions, and collective action to mitigate greenhouse gas emissions, adapt to changing conditions, and promote sustainability and resilience.

3.1 Mitigation technologies

Mitigation strategies and technologies refer to the various approaches and tools used to reduce or prevent greenhouse gas (GHG) emissions, thus mitigating the impacts of climate change. These strategies and technologies play a crucial role in achieving the goals of the Paris Agreement, which aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 degrees Celsius. [13]

These strategies can be categorized respect to the single cause of GHG emission that must be mitigated. Therefore, as seen in the last chapter, industrial, energy and transportation sectors, agriculture and land use are the main contributors to the climate change and so the ones in which is necessary to adopt mitigation strategies and technologies.

As regards the energy sector, the mitigation technologies that play a significant role are focused on replace fossil fuel as energy source with renewable energy technologies such as solar, wind, hydroelectric, and geothermal power, which harness naturally replenishing sources to generate electricity with minimal greenhouse gas emissions. These technologies help reduce reliance on fossil fuels, which are major contributors to climate change. Continued advancements in renewable energy systems, including improved efficiency and cost-effectiveness, are essential for transitioning to a low-carbon energy sector. Here are presented some of the key renewable energy technologies [15]:

1. Solar Energy: Solar energy technology utilizes sunlight to generate electricity and heat. Photovoltaic (PV) systems convert sunlight directly into electricity using solar panels composed of semiconducting materials. Concentrated Solar Power (CSP) systems use mirrors or lenses to concentrate sunlight onto

a receiver, generating high-temperature heat that is used to produce steam and drive a turbine for electricity generation. Theoretical advancements include the development of high-efficiency solar cells.

2. Wind Energy: Wind turbines convert the kinetic energy of the wind into mechanical energy, which is then transformed into electricity through a generator. Onshore wind farms are typically installed on land, while offshore wind farms are situated in bodies of water such as oceans or lakes. Advances in wind turbine design and offshore wind technology have significantly increased the efficiency and capacity of wind energy systems.

3. Hydropower: Hydropower harnesses the energy of flowing or falling water to generate electricity. It involves the construction of dams or the use of river currents or tidal movements. The force of the water drives turbines, which in turn produce electricity. Hydropower is one of the oldest and most widely used renewable energy technologies, with large-scale hydroelectric plants and small-scale run-of-the-river or micro-hydro systems. Theoretical advancements include low-head hydroelectric systems that can harness the energy from small water streams.

4. Geothermal Energy: Geothermal energy utilizes the natural heat from within the Earth to generate electricity or provide direct heating and cooling. Geothermal power plants extract hot water or steam from underground reservoirs and use it to drive turbines, generating electricity. Geothermal heat pumps leverage the stable temperature of the Earth to provide heating and cooling for buildings. Theoretical advancements include enhanced geothermal systems (EGS) that enable the extraction of heat from deeper and less permeable rock formations.

5. Biomass Energy: Biomass energy involves the conversion of organic matter, such as agricultural residues, forest residues, or dedicated energy crops, into usable forms of energy. Biomass can be burned directly to produce heat or converted into biogas through anaerobic digestion. Biomass can also be used to produce liquid biofuels like ethanol and biodiesel, which can be used in transportation or as a substitute for fossil fuels in various applications.

6. Ocean Energy: Ocean energy technologies harness the energy from waves, tides, and thermal gradients in the ocean. Wave energy converters capture the kinetic energy of ocean waves and convert it into electricity. Tidal energy systems utilize the ebb and flow of tides to generate power. Ocean thermal energy conversion (OTEC) systems exploit the temperature difference between warm surface waters and cold deep waters to produce electricity.

These renewable energy technologies offer vast potential for reducing greenhouse gas emissions and transitioning to a more sustainable energy system. According to the IPCC AR6 report, increasing the share of renewable energy in the global energy mix is vital for achieving net-zero emissions by mid-century. However, each technology has its own specific considerations, such as resource availability, cost, infrastructure requirements, and environmental impacts. The continued development and deployment of these technologies, along with supportive policies and investment, are important for accelerating the global energy transition toward a low-carbon future.

Another renewable energy technology, defined crucial for the transition to low-carbon energy sector, is the nuclear power which is a low-carbon energy source that generates electricity through nuclear reactions from uranium as raw material. Although it has its own challenges and considerations, nuclear power provides a stable and reliable energy supply with minimal greenhouse gas emissions. Advanced nuclear reactor designs, such as small modular reactors and fusion technologies, are being explored to enhance safety, efficiency, and waste management. Theoretical advancements include Generation IV reactor concepts, such as molten salt reactors and small modular reactors. [15]

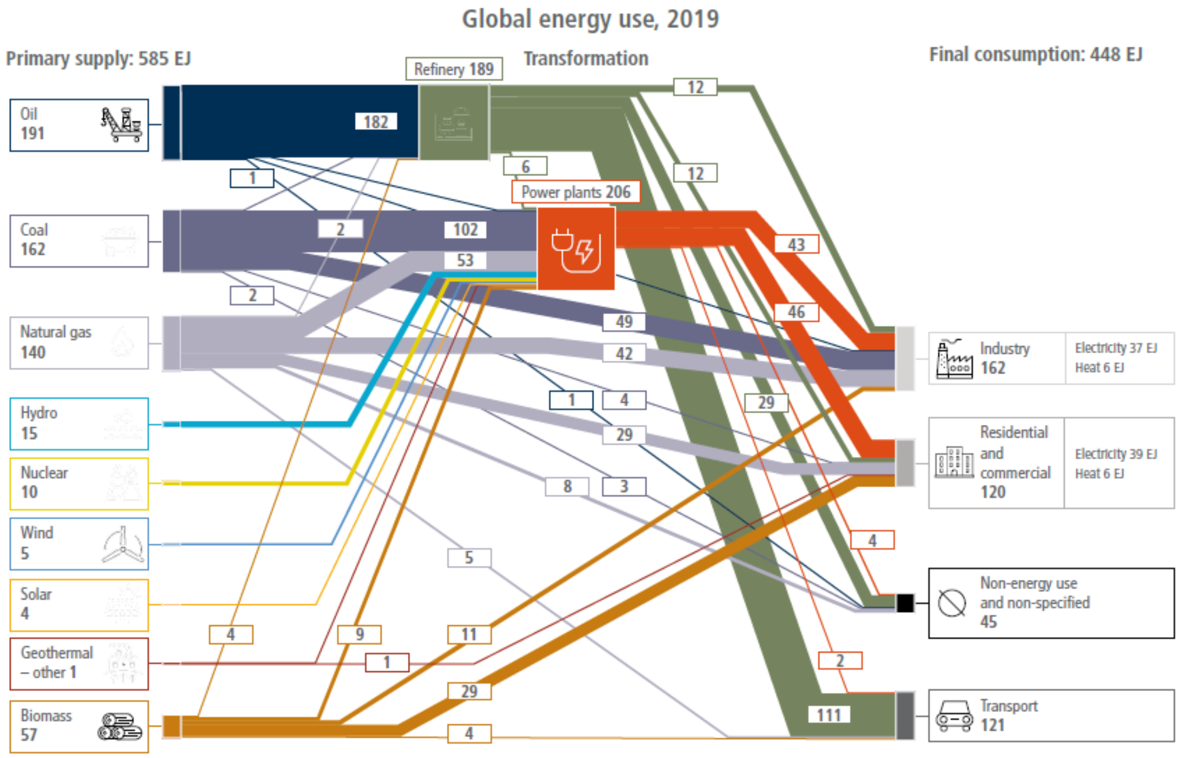


Figure TS.11 | Global energy flows within the 2019 global energy system (top panel) and within two illustrative future, net-zero CO_2 emissions global energy system (bottom panels).

Figure 13. Global energy use, 2019

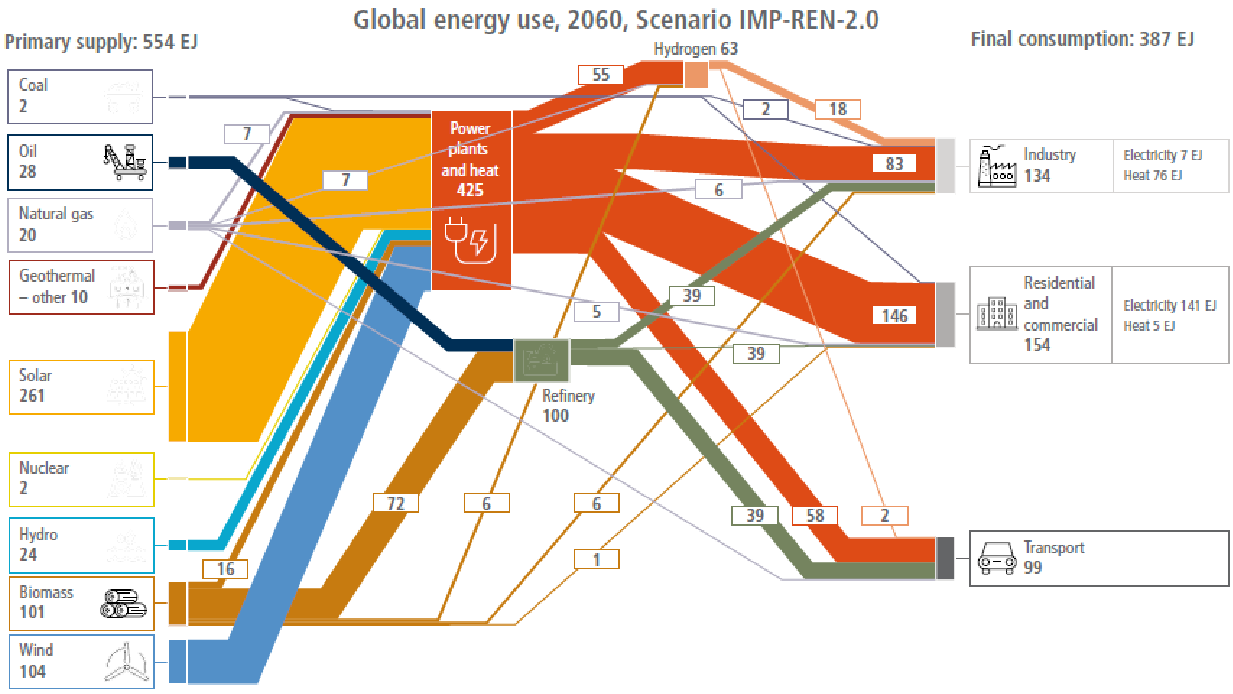


Figure 14. Global energy use, 2060, scenario

Renewable energy technologies must be coupled with energy storage and energy efficient technologies to be effective. Energy storage technologies are critical for optimizing the integration of renewable energy sources into the grid. They enable the capture and storage of excess energy generated during peak production periods and its release during high demand, thereby ensuring a stable and reliable power supply. Battery storage, pumped hydro storage, and thermal energy storage are the key energy storage technologies developed and deployed.

- Battery Storage: Lithium-ion batteries are widely used for energy storage, both at the utility scale and in electric vehicles. Theoretical advancements focus on improving battery efficiency, lifespan, and reducing costs.
- Pumped Hydro Storage: Pumped hydro storage systems use excess electricity to pump water to a higher elevation and then release it to generate electricity during peak demand. Theoretical advancements explore the use of abandoned mines and underground reservoirs for pumped hydro storage.
- Thermal Energy Storage: Thermal energy storage systems store excess heat or cold for later use, improving the efficiency of heating and cooling applications. Theoretical advancements focus on the development of advanced phase-change materials and innovative storage designs.

Improving energy efficiency across sectors is another effective mitigation strategy. By reducing energy demand and optimizing energy use, efficiency measures can reduce GHG emissions and enhance sustainability. The IPCC highlights the importance of energy-efficient buildings, industrial processes, transportation, and appliances in achieving emission reduction targets. Improving energy efficiency across sectors is a cost-effective strategy for reducing greenhouse gas emissions. Energy-efficient technologies and practices aim to minimize energy wastage and enhance overall energy productivity. Examples include efficient appliances, building insulation, advanced building management systems and LED lighting, smart grids, and industrial efficiency implementing energy-efficient processes, optimizing production, and utilizing waste heat recovery systems reduce energy consumption and emissions in industries such as manufacturing, chemicals, and mining.

Developing sustainable transportation systems is also vital, as mitigation strategy, to reduce emissions from the transportation sector, which is a significant contributor to greenhouse gas emissions. Electric vehicles (EVs), hydrogen fuel cell vehicles, hybrid vehicles, biofuels, and improved fuel efficiency in automobiles, as well as the development sustainable public transportation systems are among the technologies driving the transition to low-carbon transport.

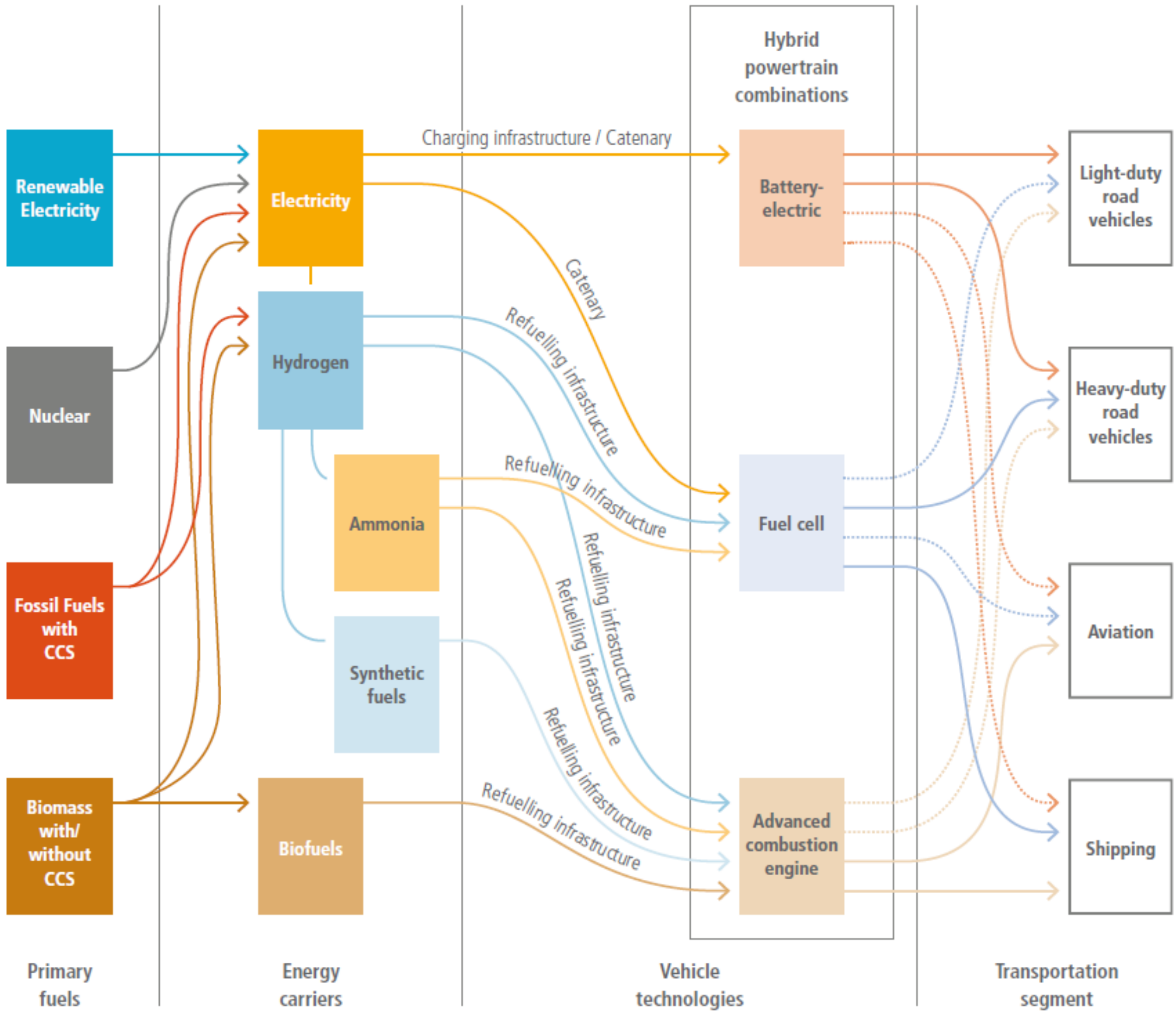


Figure 10.2 | Energy pathways for low-carbon transport technologies. Primary energy sources are shown in the far left, while the segments of the transport system are in the far right. Energy carriers and vehicle technologies are represented in the middle. Primary pathways are shown with solid lines, while dotted lines represent secondary pathways.

Figure 15. Energy pathways for low-carbon transport technologies

Shifting from fossil fuel-based technologies to electrified systems powered by renewable energy is a significant mitigation pathway. Electrifying transportation, heating, and industrial processes can significantly reduce emissions. Additionally, decarbonizing sectors like industry and agriculture using low-carbon alternatives and carbon capture technologies can help achieve emission reductions.

Carbon Capture, Utilization, and Storage (CCUS) technologies involve capturing CO2 emissions from power plants and industrial processes, transporting it, and storing it underground or using it in various applications. The IPCC recognizes CCUS as a key technology for achieving deep emissions reductions, particularly in sectors where decarbonization is challenging, such as heavy industries. The steps of the CCUS technologies are shown in the figure below.

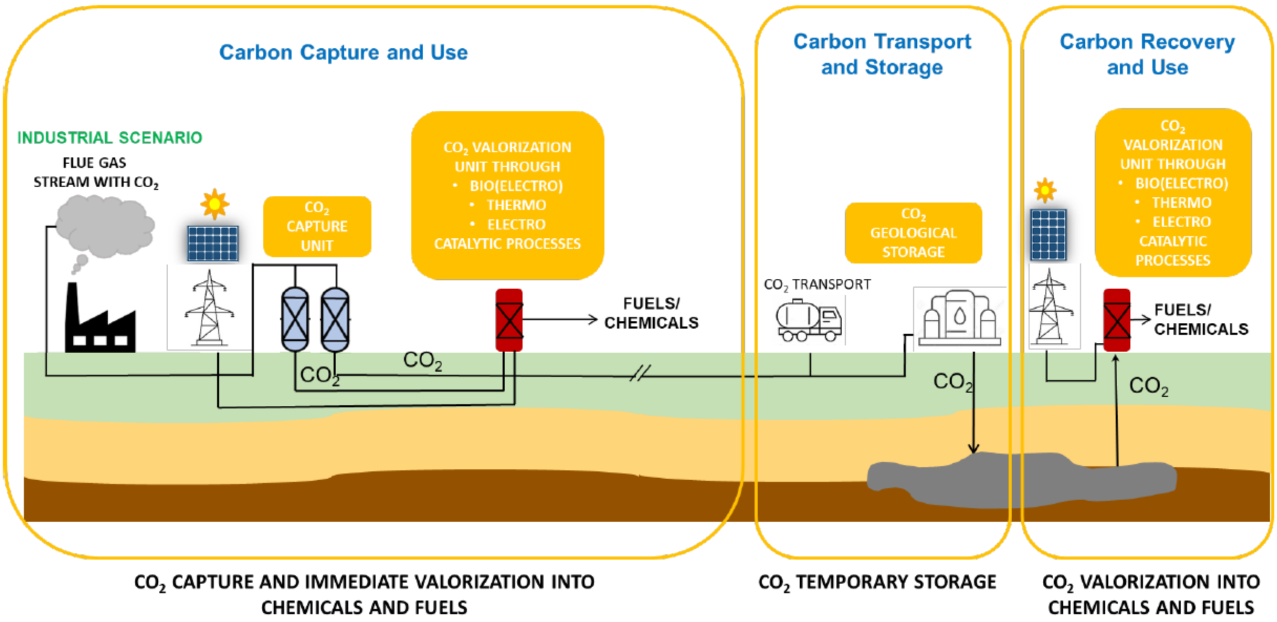


Figure16. Carbon Capture, Utilization, and Storage (CCUS)

Carbon Capture and Storage (CCS) technologies are the crucial step to reduce CO2 emissions and concentrations in atmosphere while allowing for the continued use of fossil fuels during the transition to a low-carbon economy. Ongoing research is focused on improving the efficiency and scalability of CCS technologies, here some examples [16]:

1. Post-Combustion Capture:

- Flue Gas Capture: Post-combustion capture involves capturing CO2 from the flue gases emitted after the fuel has been burned. The flue gases are first treated to remove impurities such as sulphur dioxide (SO2) and nitrogen oxides (NOx). Then, the CO2 is separated from the flue gases using various methods such as chemical solvents, adsorption processes, or membrane technologies. Various solvents or sorbents, such as amines (e.g., monoethanolamine - MEA), are commonly used to absorb CO2. The solvent absorbs the CO2, forming a rich solution that is then heated to release the captured CO2 for further processing.

- CO2 Separation: The captured CO2 is then separated from the solvent using heat or pressure, leaving behind a concentrated CO2 stream.
- Compression and Purification: The released CO2 is compressed to a supercritical state, where it becomes a dense fluid with a smaller volume for transportation and storage. The CO2 is then purified to remove any remaining impurities before it is transported.
- Storage or Utilization: The compressed CO2 is either transported via pipelines or ships to suitable storage sites, such as deep saline aquifers or depleted oil and gas reservoirs, for permanent storage. Alternatively, it can be used in various industrial processes, such as enhanced oil recovery (EOR) or the production of chemicals and materials.

2. Pre-Combustion Capture: Pre-combustion capture involves capturing CO2 before the fuel is burned. This technology is commonly used in integrated gasification combined cycle (IGCC) power plants and other facilities that use gasification processes. The steps involved in pre-combustion capture are:

- Gasification: The fuel, such as coal or biomass, is converted into a synthesis gas (syngas) containing mainly carbon monoxide (CO) and hydrogen (H2) through gasification.
- Shift Conversion: The CO in the syngas is reacted with steam in a shift conversion process to produce additional H2 and CO2.
- CO2 Separation: The CO2 is separated from the syngas using various technologies like pressure swing adsorption or membrane separation.
- Storage or Utilization: The separated CO2 can be stored or utilized in a manner like post-combustion capture.

3. Oxyfuel Combustion: Oxyfuel combustion involves burning fossil fuels in a mixture of oxygen and recirculated flue gases, resulting in a flue gas stream primarily composed of CO2 and water vapor. The CO2 is then captured from the flue gas using post-combustion capture technologies, while the water vapor is condensed and removed. The remaining flue gas, predominantly CO2, can be compressed, transported, and stored or utilized.

4. Carbon Capture from Industrial Processes: CCS technologies are also being developed and deployed for capturing CO2 emissions from industrial processes other than power generation. Industries such as cement production, iron and steel manufacturing, and hydrogen production emit significant amounts of CO2. Different capture methods can be employed depending on the specific industry and process.

5. Direct Air Capture (DAC): DAC technologies capture CO2 directly from the atmosphere. Theoretical advancements focus on improving the efficiency and scalability of DAC systems. Real-world examples include

the Climeworks DAC plant in Iceland, which captures CO2 and stores it underground or uses it for industrial purposes. [17]

It's important to note that CCS technologies are still in various stages of development and deployment. Large-scale CCS projects, such as the Petra Nova project in the United States, the Gorgon Project in Australia, and the Sleipner field in Norway, have demonstrated the feasibility of CCS at commercial scales. However, there are challenges to address, including the high costs of implementation, the energy penalty associated with capturing and compressing CO2, and the need for suitable storage sites. To advance CCS technologies, ongoing research focuses on developing more efficient and cost-effective capture processes, exploring alternative sorbents and solvents, optimizing CO2 transportation and storage methods, and improving the overall sustainability of CCS systems.

The IPCC also emphasizes the importance of sustainable land management and afforestation/reforestation efforts. Proper land use and sustainable land practices, such as rotational grazing, agroforestry, and soil conservation measures, reduces emissions from agriculture and promotes carbon sequestration. Forest management, protecting existing forests, planting trees in deforested areas or restoring degraded forests helps sequester carbon dioxide through photosynthesis, mitigating emissions and preserving biodiversity. Implementing sustainable agriculture practices can enhance carbon sequestration and reduce deforestation, which contributes to significant emissions. [11]

In this context, sustainable agricultural practices are at the same time mitigation technologies and innovations for adaptation strategies to increase resilience. Precision Agriculture techniques utilize advanced technologies, such as satellite imagery, sensors, and data analytics, to optimize fertilizer use, improve irrigation systems and usage of water, permit methane capture from livestock and enhance sustainable crop management, reducing emissions and improving resource efficiency, while ensuring food security.

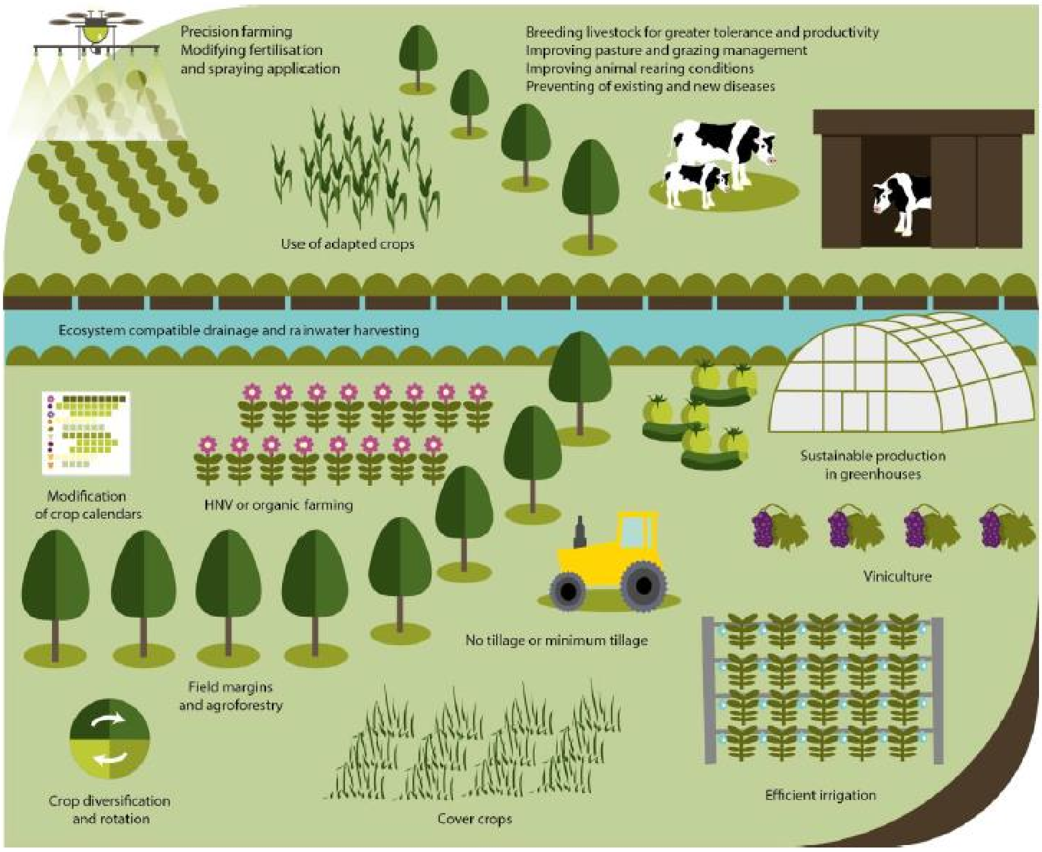


Figure 17. Precision Agriculture

3.2 Adaptation strategies

Adaptation strategies refer to the measures and actions that can be taken to manage the risks and impacts associated with climate change. These strategies aim to enhance resilience and reduce vulnerability to climate-related hazards and changes in order to safeguard human and natural systems.

First, climate change is already happening, and its impacts are being felt across the globe. Rising temperatures, changing precipitation patterns, increased frequency and intensity of extreme weather events, and sea-level rise, as seen in the first chapter, pose significant risks to human and natural systems. Adaptation strategies help communities and ecosystems cope with these changes ensuring their long-term survival and well-being.

Furthermore, the impacts of climate change are not evenly distributed, and vulnerable communities and regions are disproportionately affected. Adaptation strategies prioritize addressing the needs and vulnerabilities of these marginalized groups, aiming to ensure equity and social justice in climate action. This involves engaging with local communities, respecting indigenous knowledge, and empowering the most vulnerable populations to participate in decision-making processes.

Adaptation strategies also contribute to building resilience in socio-ecological systems. By enhancing the capacity to withstand and recover from climate-related shocks and stresses, communities and ecosystems become more robust and better equipped to adapt to future changes. This resilience is essential for maintaining vital services, such as food security, water availability, and infrastructure functionality, even in the face of climate uncertainties.

Moreover, adaptation strategies offer co-benefits beyond climate resilience. Many adaptation measures contribute to sustainable development goals, such as poverty alleviation, biodiversity conservation, and public health improvement.

The impacts of climate change and the appropriate adaptation strategies vary across regions and sectors. Local knowledge, context-specific assessments, and stakeholder engagement are crucial for designing and implementing effective adaptation measures.

Adaptation is essential because not all climate change impacts can be avoided or mitigated solely through emission reduction efforts. Even with aggressive mitigation measures, some level of climate change is inevitable due to the cumulative effects of past emissions. Therefore, adaptation serves as a complementary approach to manage the risks that cannot be eliminated entirely. In the figure below is presented the relationship between mitigation technologies and adaptation strategies. [12]

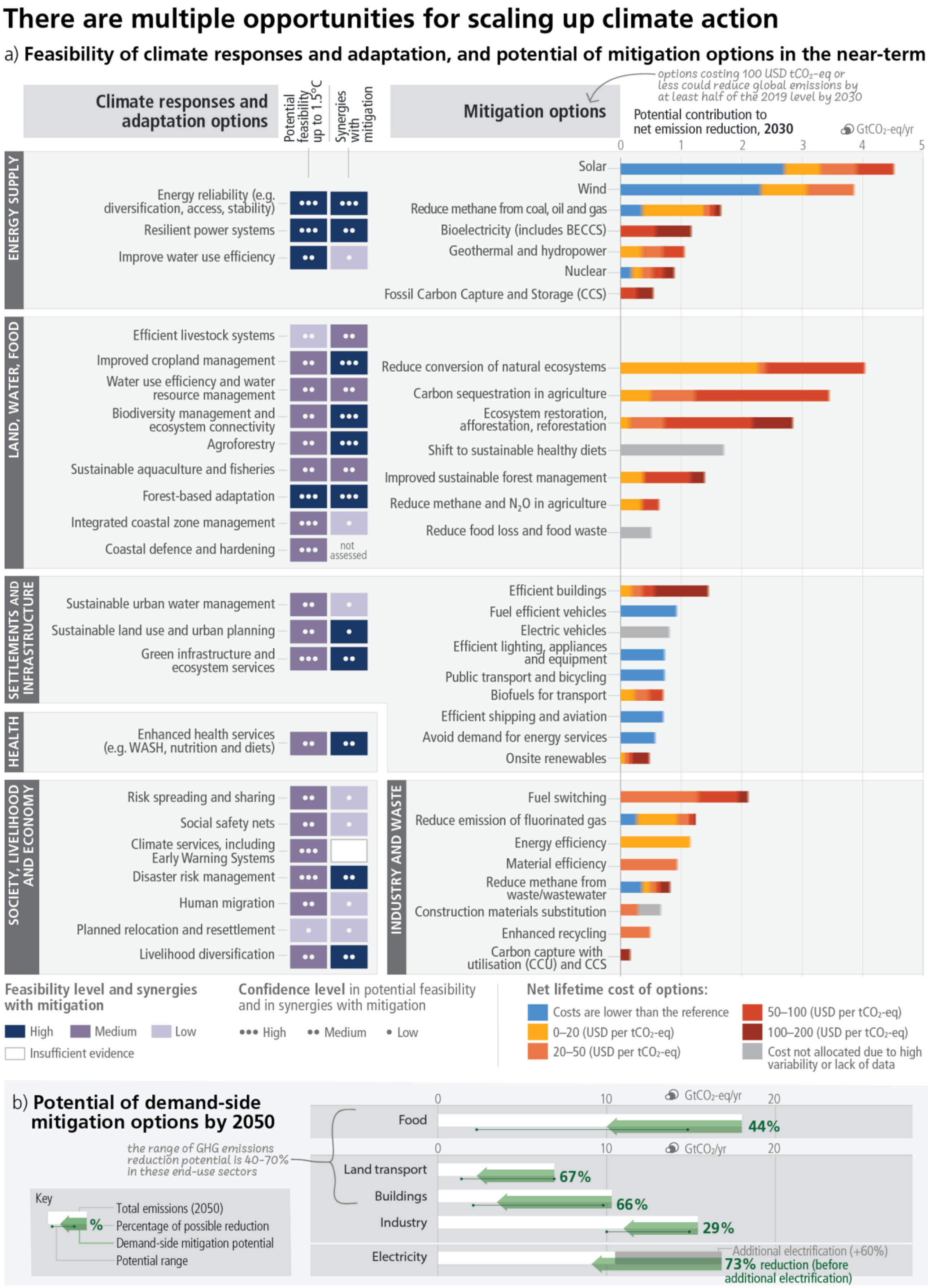


Figure 18. Relationship between mitigation and adaptation strategies

The IPCC AR6 report provides in-depth analysis, case studies, and recommendations on adaptation strategies across various sectors, regions, and ecosystems. It emphasizes the need for integrating adaptation into development planning and decision-making processes, considering equity and social justice dimensions, and fostering multi-level governance and collaboration. Some key adaptation strategies and technologies provided by the IPCC are [12]:

1. Climate Information Services and Early Warning Systems:
   - Climate Data and Modelling: information services provide timely and accurate climate data, forecasts, and projections to support decision-making at various levels. Climate models and scenario analysis provide valuable insights into potential climate impacts, helping communities and policymakers develop appropriate adaptation strategies.
   - Early Warning Systems: Early warning systems integrate climate and weather information to provide timely alerts and risk assessments for various hazards such as floods, storms, and heatwaves. By disseminating warnings to communities, emergency services can take proactive measures to mitigate risks, evacuate vulnerable populations, and reduce the impact of extreme events.
2. Climate-Resilient Infrastructure:
   - Flood Management: implementing flood control measures, such as levees, flood barriers, and improved drainage systems, helps protect communities and infrastructure from increased flood risks.
   - Coastal Protection: Constructing seawalls, breakwaters, and other coastal defence structures helps mitigate coastal erosion and reduces the impacts of sea-level rise and storm surges.
   - Resilient Building Design: Designing buildings to withstand extreme weather events and changing climate conditions is essential. This includes using durable and renewable materials, elevating structures in flood-prone areas, incorporating natural ventilation and cooling systems, and integrating renewable energy technologies to enhance resilience and reduce dependence on external resources during disruptions.
   - Heat-Resilient Buildings: Constructing buildings with better insulation, reflective roofs and efficient cooling systems helps reduce heat stress and improve indoor comfort during heatwaves. Creating urban green corridors and designing buildings with green roofs can also mitigate the urban heat island effect.
   - Resilient Transport Systems: Designing transport infrastructure to withstand extreme weather events, integrating climate risk assessments into transport planning, and promoting sustainable modes of transport contribute to climate resilience.
   - Nature-Based Solutions: Nature-based solutions involve using natural systems and processes to provide climate resilience. For example, incorporating green spaces, constructing green roofs and permeable pavements in urban areas helps absorb and manage rainfall, reducing the risk of

flooding. Additionally, restoring wetlands and creating buffer zones along coastlines can protect against storm surges and erosion.

- Water Resource Management: Implementing integrated water resource management approaches ensures sustainable water supply in the face of changing precipitation patterns. This includes rainwater harvesting, water storage systems, and efficient irrigation practices that optimize water use in agriculture and reduce vulnerability to droughts.

Building resilient infrastructure is essential to withstand and adapt to climate change impacts. This includes considering climate change projections in the design, construction, and maintenance of infrastructure, such as roads, bridges, buildings, and water supply systems. Retrofitting existing infrastructure to be more resilient can also minimize risks and damages.

3. Ecosystem-based Adaptation:
   - Coastal Ecosystem Restoration: Protecting and restoring coastal ecosystems such as mangroves, coral reefs, and salt marshes provides natural barriers against storm surges, erosion, and sea-level rise, while also preserving biodiversity.
   - Protected Areas and Biodiversity Conservation: Establishing, preserving, and effectively managing protected areas helps preserve biodiversity, conservation of species, maintain ecosystem services, and enhance resilience to climate change impacts. Protected areas can serve as natural buffers against extreme events, provide habitats for species migration, and support ecosystem functioning.
   - Sustainable Forest Management: Implementing sustainable forest management practices, such as selective logging, afforestation, and forest restoration, helps maintain forest ecosystems' capacity to sequester carbon, regulate water flows, and provide other essential services. This contributes to climate resilience while supporting local livelihoods.
   - Climate-Smart Agriculture: Climate-smart agricultural practices aim to enhance productivity, promote adaptive capacity, and reduce greenhouse gas emissions. Techniques include agroforestry, crop diversification, precision farming, soil conservation, and efficient water management. These practices improve farmers' resilience to climate-related risks and contribute to sustainable food production.

Ecosystem-based adaptation (EbA) focuses on the conservation, restoration, and sustainable management of ecosystems to enhance resilience and reduce the vulnerability of both human and natural systems. This approach recognizes the role of ecosystems in providing essential services, such as flood protection, water regulation, and habitat preservation, which can be crucial for climate change adaptation.

4. Risk Assessment and Management: Systematic risk assessment is crucial for understanding the vulnerabilities, exposure, and potential impacts of climate change on various sectors, regions, and communities. Risk management strategies involve identifying and prioritizing adaptation measures, allocating resources, and implementing actions to reduce climate-related risks.

5. Social and Institutional Adaptation:

- Education and Awareness: Promoting climate change education, raising awareness about climate risks, and encouraging behaviour change toward sustainable practices contribute to individual and community resilience.
- Health Adaptation: Strengthening healthcare systems, improving disease surveillance, and implementing heatwave preparedness measures help address the health impacts of climate change, including increased heat-related illnesses and the spread of vector-borne diseases.
- Community-Based Adaptation: Engaging local communities in the adaptation process is essential. Community-based adaptation involves empowering communities to identify their vulnerabilities, develop context-specific strategies, and implement actions that build resilience. This can include livelihood diversification, capacity building, and knowledge-sharing platforms.

6. Financial Mechanisms and Insurance: Access to financial resources is vital for implementing adaptation strategies. Establishing dedicated funds, international financing mechanisms, and innovative financial instruments can help support adaptation efforts, particularly in developing countries. Insurance mechanisms, including climate risk insurance and microinsurance, can provide financial protection against climate-related losses and support recovery efforts.

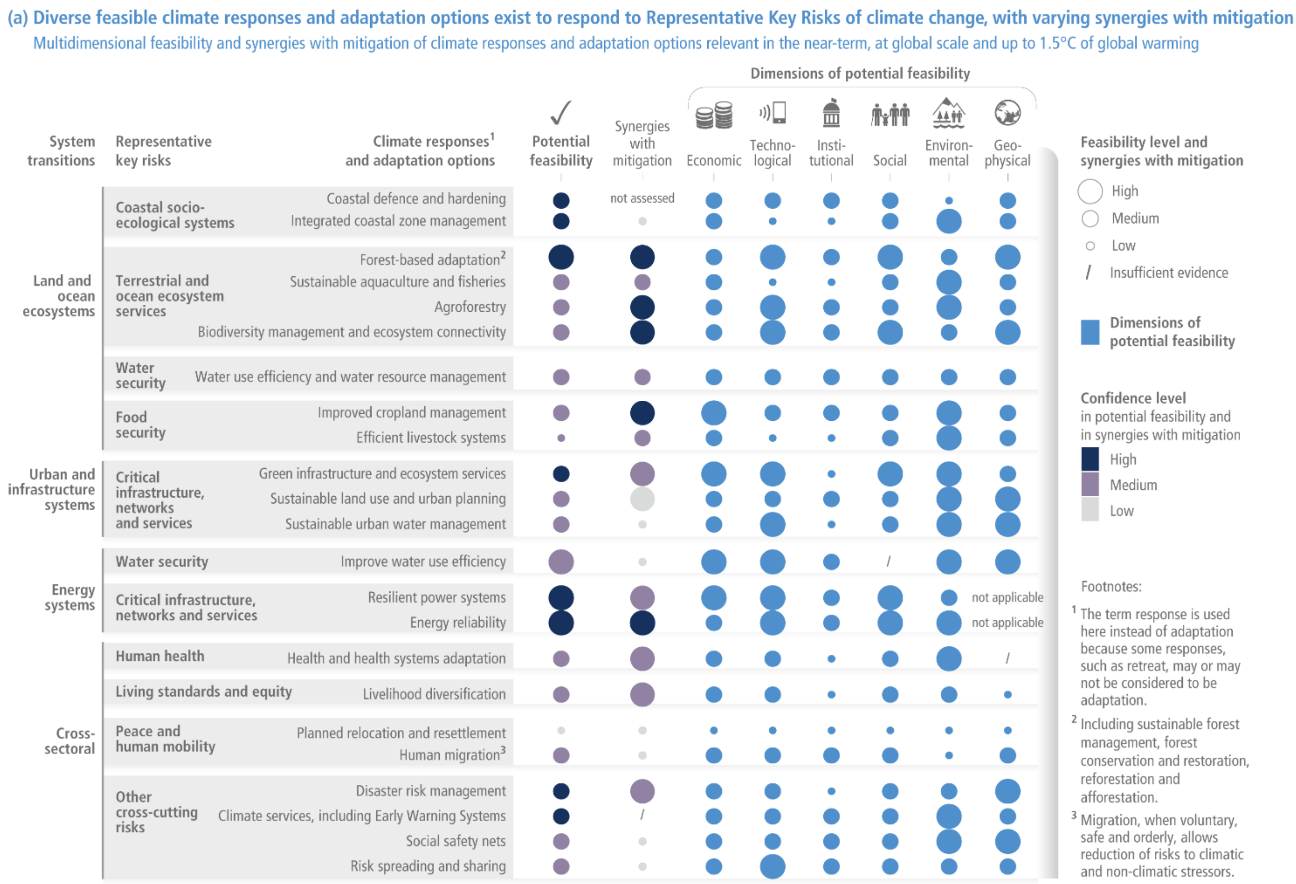


Figure 19. Adaptation options

In conclusion, in this chapter, the possible solutions, mitigation and adaptation technologies and strategies, to face the problem of climate change, were presented. It is crucial to recognize that addressing climate change requires also systemic transformations and reimagining our relationship with nature. Technological innovations and policy measures alone will not be sufficient. There is the need of a shift in societal values, consumption patterns, and economic models towards sustainability, resilience, and regenerative practices. This requires collective action, individual responsibility, and engagement at all levels of society.

It is important to underline the problems related to social acceptance and the economic engagement. At present day, economic and social structures seem still oriented to the linear economy, and fossil fuel dependency; this is due to the difficult of changing the global industrial social structure in few decades or years to face a problem that derives from centuries of consolidated behaviours, governments, and production and consumption structures.

Despite the overwhelming challenges, there are reasons for optimism. The growing momentum of climate action, coupled with advancements in renewable energy technologies, offers opportunities for a sustainable and prosperous future. The transition to a low-carbon economy can create new jobs, foster innovation, and enhance energy security.

Moreover, addressing climate change is not just about mitigating its impacts but also recognizing the potential for co-benefits. Investments in renewable energy, energy efficiency, and sustainable agriculture can improve air quality, enhance public health, and foster community resilience. By taking an integrated approach, it is possible to unlock multiple positive outcomes that extend beyond climate change mitigation.

4. Ecosystems and environmental damage

4.1 Ecosystems and climate change

Ecosystems, as outlined in the previous chapters, play a crucial role in mitigating and adapting to climate change. Ecosystems provide a wide range of services, known as ecosystem services, that are vital for human well-being and the functioning of the planet.

One of the key roles of ecosystems is their ability to sequester and store carbon dioxide. Terrestrial ecosystems, including forests, grasslands, and wetlands, act as carbon sinks, absorbing CO2 from the atmosphere through photosynthesis and storing it in vegetation, soils, and organic matter. IPCC AR6 recognizes that these natural sinks are essential for achieving climate stabilization goals, as they currently absorb around 30% of anthropogenic CO2 emissions.

Furthermore, ecosystems enhance climate resilience by providing natural buffers against climate-related hazards. Forests, for instance, play a crucial role in regulating rainfall, preventing erosion and landslides, and maintaining water cycles. Wetlands act as natural buffers against storms and floods by absorbing excess water. Coastal ecosystems, such as mangroves, salt marshes, and coral reefs, serve as natural barriers that protect coastal communities from storm surges and sea-level rise. These ecosystems act as "blue carbon" sinks, sequestering carbon and providing additional climate benefits. IPCC AR6 highlights the importance of conserving and restoring these ecosystems to enhance climate resilience.

Additionally, ecosystems regulate local and regional climates through evapotranspiration, which is the process of water movement from the land to the atmosphere through plants. Forests, for example, release moisture into the air, creating cooler and more humid microclimates. This cooling effect helps moderate temperatures, reduce heatwaves, and improve air quality in urban areas. The loss or degradation of ecosystems can disrupt these climate regulation mechanisms and exacerbate the impacts of climate change.

Ecosystems also support livelihoods and provide socio-economic benefits to communities. IPCC AR6 emphasizes the critical role of nature-based solutions, discussed in the last chapter, which harness the power of ecosystems, in achieving sustainable development goals. For instance, sustainable agricultural practices that promote ecosystem health and biodiversity can enhance food security and rural livelihoods while mitigating climate change.

However, climate change poses significant threats to ecosystems. Rising temperatures, changes in precipitation patterns, and extreme weather events can disrupt ecological processes, leading to the degradation and loss of habitats, species extinction, and reduced ecosystem functioning. IPCC AR6 warns that without immediate and ambitious action to mitigate greenhouse gas emissions, ecosystems will face unprecedented risks, compromising their ability to provide essential services.

The impacts of climate change and the potential damages associated with these changes vary on different ecosystems. Here, different types of ecosystems and their vulnerabilities to climate change based on IPCC reports are presented [12].

1. Terrestrial Ecosystems: Terrestrial ecosystems include forests, grasslands, shrublands, and tundra. Climate change impacts on these ecosystems can result in alterations in vegetation composition, species distribution, and ecosystem functioning. Rising temperatures and changing precipitation patterns can lead to increased frequency and intensity of droughts, heatwaves, and wildfires, posing significant risks to forest health and biodiversity. IPCC reports also highlight that melting permafrost in tundra regions can release large amounts of stored carbon, exacerbating global warming.

2. Coastal and Marine Ecosystems: Coastal and marine ecosystems, such as mangroves, coral reefs, seagrasses, and salt marshes, are highly vulnerable to climate change impacts. Rising sea levels, ocean acidification, and increased water temperatures pose substantial risks to these ecosystems. IPCC reports emphasize that coral reefs, for example, face severe degradation and increased susceptibility to bleaching events due to warmer and more acidic oceans. Loss of these ecosystems not only affects biodiversity but also compromises their ability to provide coastal protection and sustain fisheries.

3. Freshwater Ecosystems: Freshwater ecosystems, including rivers, lakes, wetlands, and glaciers, are also susceptible to climate change. Changes in precipitation patterns can affect water availability, alter hydrological cycles, and cause shifts in the distribution of species. IPCC reports highlight that reduced snowpack and glacier melting contribute to changes in river flows, threatening water supplies for human populations, agriculture, and ecosystems. Furthermore, increased water temperatures and altered nutrient inputs can disrupt freshwater biodiversity and ecosystem functioning.

4. Arctic and Polar Ecosystems: The Arctic and polar regions are experiencing some of the most rapid changes due to climate change. Melting sea ice, thawing permafrost, and warming temperatures are profoundly affecting these ecosystems. IPCC reports warn that loss of sea ice habitat poses significant challenges for ice-dependent species, such as polar bears and seals. Thawing permafrost can release stored carbon and methane, amplifying global warming. Changes in these ecosystems also have broader implications for global climate feedbacks and sea-level rise.

5. Urban Ecosystems: Urban areas, although human-made, also have distinct ecosystems that can be impacted by climate change. Urban heat island effect, increased heatwaves, and altered precipitation patterns can exacerbate heat stress, air pollution, and water management challenges in cities. IPCC reports highlight the importance of integrating nature-based solutions, such as urban green spaces and green infrastructure, to enhance climate resilience and improve urban life quality.

These ecosystems are interconnected, and changes in one ecosystem can have cascading effects on others. The IPCC reports emphasize the urgent need for climate mitigation and adaptation measures to protect these ecosystems and their associated services.

The adaptation strategies vary for the different ecosystems listed earlier. For terrestrial ecosystems adaptation strategies include forest management practices, such as sustainable logging, reforestation, and afforestation, to enhance ecosystem resilience and carbon sequestration. Implementing measures to reduce the risk of wildfires, such as prescribed burning and improved fire management. [11]

Adaptation strategies for coastal and marine ecosystems involve the conservation and restoration of these ecosystems, such as mangrove planting, seagrass restoration, and the creation of marine protected areas. IPCC reports highlight the significance of implementing integrated coastal management approaches that consider the impacts of climate change, such as incorporating sea-level rise projections into coastal planning and infrastructure development.

Adaptation strategies for freshwater ecosystems include managing water resources more effectively, improving water storage and distribution systems, and protecting and restoring wetlands. IPCC reports emphasize the need for adaptive water management practices that account for changes in precipitation patterns and water availability. Restoring and preserving riparian zones can also help maintain water quality and support freshwater biodiversity.

Adaptation strategies for Arctic and polar ecosystems focus on reducing greenhouse gas emissions to mitigate further warming. Implementing measures to reduce black carbon and other short-lived climate pollutants can slow down the rate of warming in these regions. Additionally, IPCC reports highlight the importance of protecting key habitats, such as sea ice, and managing human activities, such as shipping and resource extraction, to minimize impacts on these fragile ecosystems.

Adaptation strategies for urban ecosystems involve incorporating nature-based solutions into urban planning and design. This includes creating green spaces, rooftop gardens, and urban forests to mitigate the urban heat island effect and improve air quality. Implementing sustainable water management practices, such as rainwater harvesting and the use of permeable surfaces, can also enhance resilience to changing precipitation patterns. [12]

In addition to these specific ecosystem-based adaptation strategies, IPCC reports emphasize the importance of mainstreaming adaptation into broader policies and planning processes. This includes integrating climate change considerations into land-use planning, ecosystem restoration programs, and natural resource management.

It is crucial to adapt adaptation strategies to the specific characteristics and vulnerabilities of each ecosystem, considering the local context and involving local communities, indigenous knowledge, and stakeholders in decision-making processes.

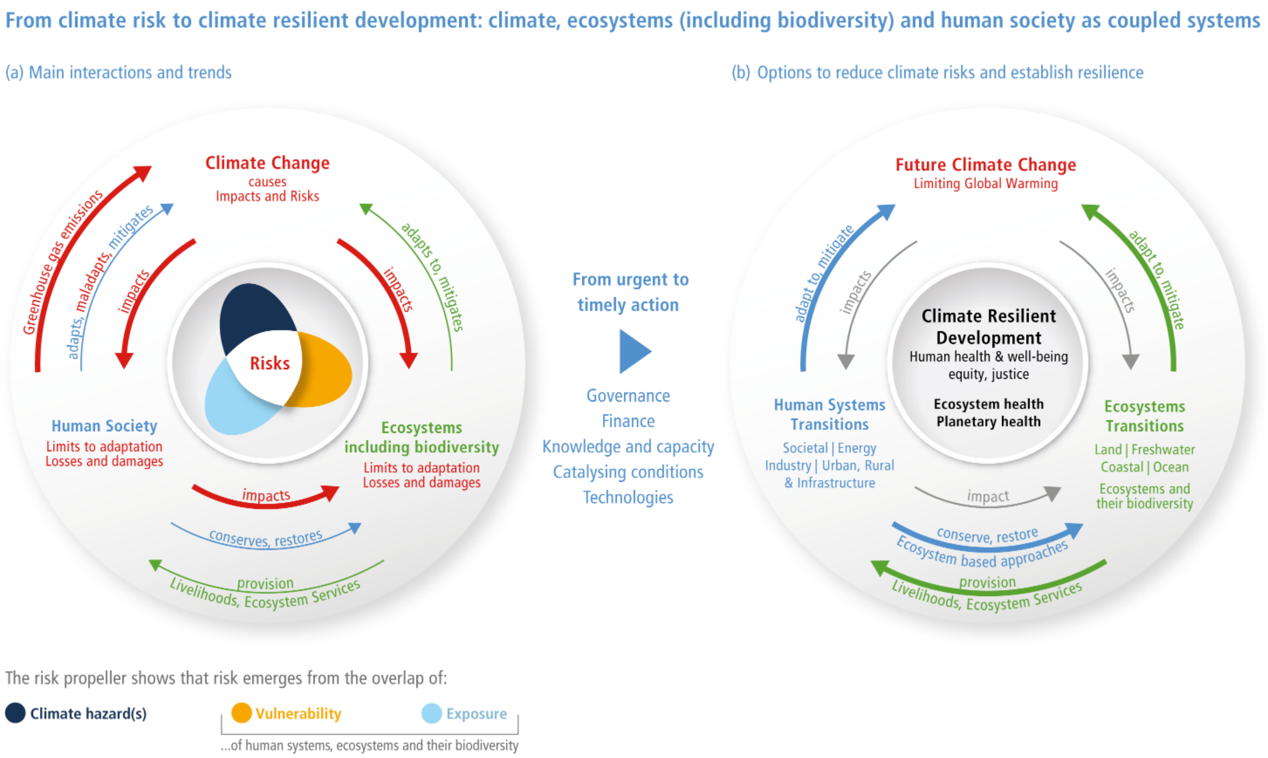


Figure 20. Climate Resilient Development

Moreover, in this context, climate change poses a significant challenge to wildlife, as it alters habitats, disrupts migration patterns, and affects species' ability to adapt. The protection of wildlife is necessary to preserve species, their habitats, and the valuable services they provide to ecosystems and human societies.

Wildlife protection involves conserving and safeguarding endangered and threatened species. This includes implementing measures to prevent illegal wildlife trade, habitat destruction, and poaching. Conservation efforts often involve habitat restoration, captive breeding programs, and protected areas to provide safe havens for these species.

Establishing protected areas and wildlife sanctuaries is crucial for wildlife protection. These areas serve as havens for species by providing undisturbed habitats, safeguarding critical breeding grounds, and allowing for natural ecological processes. Protected areas can range from national parks and reserves to community-managed conservation areas. Such areas not only protect wildlife but also provide opportunities for research, education, and ecotourism, contributing to local economies and raising awareness about the importance of biodiversity conservation.

Habitat loss and degradation due to factors like deforestation, urbanization, industrial activity, and agricultural expansion pose significant threats to wildlife populations. Conservation efforts focus on preserving and restoring habitats, creating wildlife corridors to facilitate movement between fragmented habitats, and promoting sustainable land-use practices that minimize negative impacts on wildlife and their ecosystems. [12]

Engaging local communities and raising awareness about the importance of wildlife protection are crucial aspects of conservation efforts. Involving local communities in decision-making processes, providing alternative livelihood options, and promoting sustainable practices can reduce human-wildlife conflicts and enhance support for wildlife conservation. Education and outreach programs play a vital role in fostering an understanding of the value of wildlife and inspiring actions to protect and conserve it for future generations.

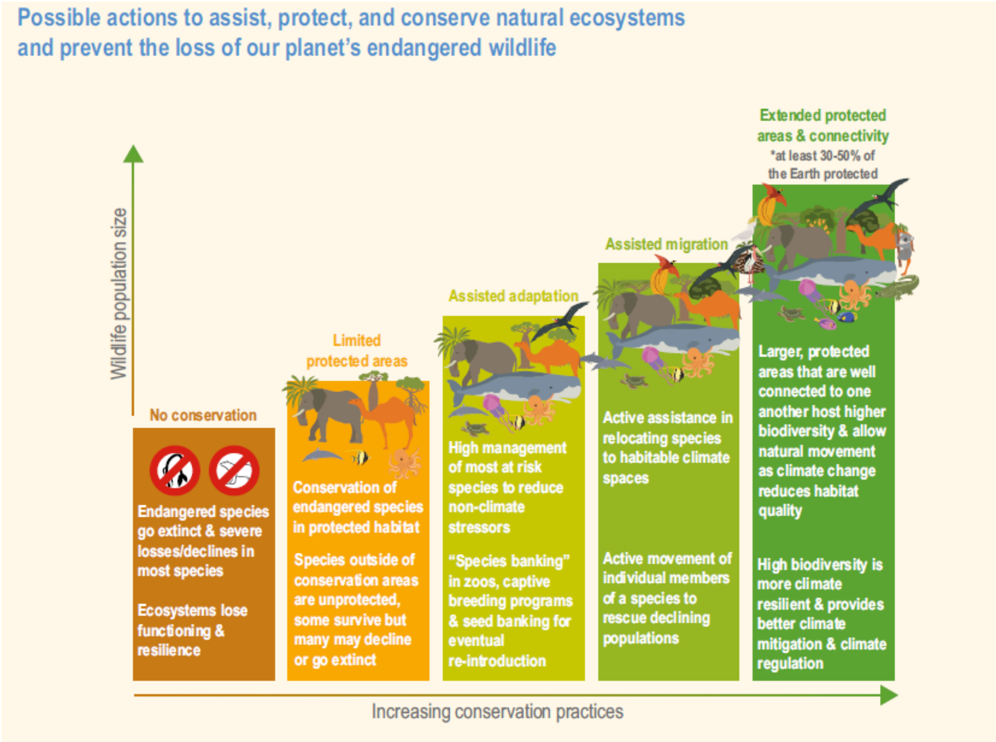


Figure FAQ2.1.1 | Possible actions to assist, protect and conserve natural ecosystems and prevent the loss of our planet's endangered wildlife in the face of continued climate change. (Inspired by the Natural Alliance website© Chris Heward/GWCT).

Figure 21. Actions to protect ecosystems and prevent loss of wildlife

4.2 Fluvial Ecosystems

The conservation and safeguarding of ecosystems, as it was outlined earlier, are critical in the context of climate change and this is particularly evident as regards river ecosystems. These ecosystems play a vital role in mitigating climate change impacts, supporting biodiversity, and providing essential ecosystem services.

River ecosystems are dynamic and complex systems where flora and fauna interact in a symbiotic relationship. This symbiosis is crucial for the functioning and resilience of the ecosystem. Aquatic plants, such as algae and macrophytes, provide habitat and food sources for various organisms, while animals, such as fish and invertebrates, help disperse seeds and pollinate plants. This interconnected web of species ensures the balance and stability of the ecosystem.

The significance of river ecosystems in climate change mitigation is highlighted, for example, in the capacity of river ecosystems to sequester carbon dioxide. Aquatic plants absorb carbon dioxide through photosynthesis, converting it into organic matter, which can then be stored in sediments. This process contributes to reducing greenhouse gas concentrations in the atmosphere.

Furthermore, the conservation of river ecosystems has broader implications for climate change adaptation. Rivers play a crucial role in regulating water flow, acting as natural buffers against extreme weather events such as floods and droughts. By maintaining healthy riparian vegetation, river ecosystems can reduce the risk and severity of these events, providing natural protection to surrounding communities and infrastructure.

In addition to their local and regional significance, river ecosystems also play a role on a global scale. Rivers transport vast amounts of organic matter, nutrients, and sediments from land to the ocean. This process influences the global carbon cycle and nutrient cycling, affecting climate patterns and ocean productivity. Therefore, the conservation of river ecosystems contributes to the overall health and resilience of the Earth's systems.

To effectively conserve river ecosystems, integrated management approaches are necessary. This includes promoting sustainable water resource management practices, minimizing pollution and habitat destruction by industrial activities and anthropogenic forces, and implementing measures to restore degraded river habitats. Collaboration among governments, communities, scientists, and conservation organizations is essential to ensure the long-term health and resilience of river ecosystems in the face of climate change.

In this context, The European Water Framework Directive (WFD) is a key piece of legislation in the European Union (EU) that aims to establish a framework for the sustainable management of freshwater resources. Adopted in 2000, the WFD provides a comprehensive approach to water management, focusing on the protection and improvement of water quality and quantity across Europe. [18]

One of the central elements of the WFD is the River Basin Management planning cycle. This cycle consists of several steps that member states of the EU are required to follow in order to achieve the objectives of the directive. The steps involved in the planning cycle are as follows:

1. Characterization of river basin: Member states assess the status of their water bodies to identify any areas where water quality or quantity falls below the desired standards, identifying pressures and estimating the impacts. Member states divide their territories into river basin districts, which serve as the geographical units for water management planning.
2. Establishment of Environmental Objectives: Environmental objectives are set for each water body within the river basin district. These objectives define the desired status of water bodies and guide the development of measures to achieve them.
3. Development of River Basin Management Plans: Member states develop river basin management plans that outline the measures to be implemented to achieve the environmental objectives. These plans must also consider the economic and social aspects of water management.
4. Public Participation and Consultation: Member states engage with stakeholders and the public during the planning process to ensure transparency and gather input from various perspectives.
5. Implementation: The measures outlined in the river basin management plans are implemented, including actions to improve water quality, reduce pollution, restore ecosystems, and manage water resources sustainably.

6. Monitoring and Review: Member states regularly monitor the status of their water bodies, assess the effectiveness of implemented measures, and review and update their river basin management plans accordingly.

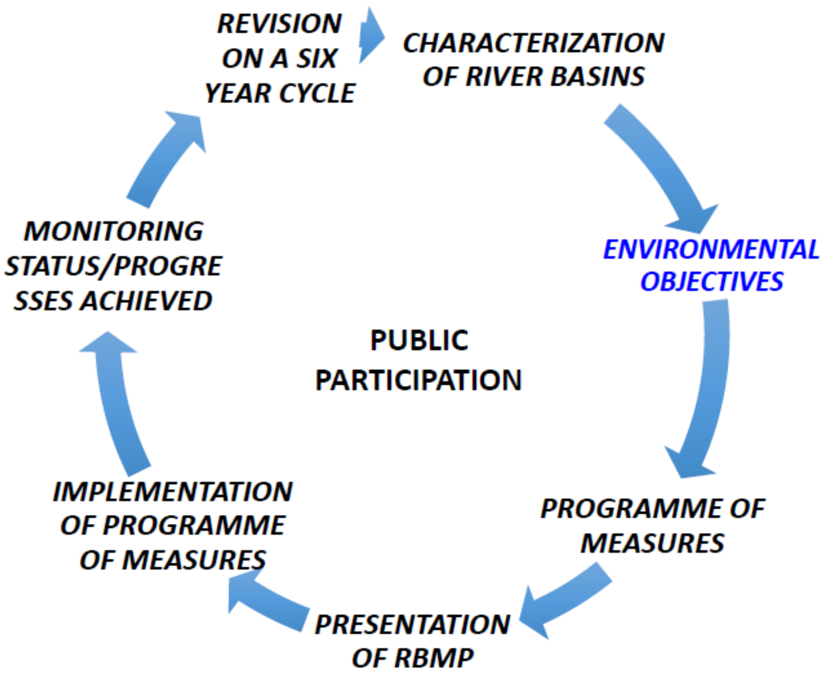


Figure 22. The planning cycle

The "status" refers to the condition or quality of a water body, which is assessed through various indicators such as physio-chemical, ecological, biological, and hydro-morphological parameters. The WFD sets out five status classifications: high, good, moderate, scarce, and bad. The objective is to achieve at least "good" status for all water bodies, with the ultimate goal of achieving "high" status wherever possible. [18]

River dynamics and hydro-morphological processes refer to the physical characteristics and processes of rivers, such as their shape, flow patterns, sediment transport, and interactions with their surrounding landscapes. The WFD recognizes the importance of maintaining natural river dynamics and hydro-morphological processes for the ecological health and functioning of water bodies. Member states are encouraged to consider these factors in their river basin management plans and implement measures to restore and maintain natural conditions where possible, considering other human uses and safety requirements.

The WFD also sets technical, economic, social, and environmental objectives to be considered in water management. Technical objectives include measures to prevent deterioration and protect and improve water quality, while economic objectives focus on promoting sustainable water use and cost-recovery principles. Social objectives involve promoting the involvement of stakeholders and the public in decision-making processes. Environmental objectives aim to achieve and maintain healthy aquatic ecosystems and protect and restore habitats and species.

The WFD emphasizes the conservation of priority habitats and species. Member states are required to take measures to prevent the deterioration of aquatic ecosystems, protect and restore habitats, and ensure the long-term survival of endangered or vulnerable species. This includes designating and managing protected areas and implementing measures to reduce the impact of human activities on these habitats and species.

Overall, the European Water Framework Directive provides a comprehensive framework for the management of freshwater resources in Europe, emphasizing the protection and sustainable use of water bodies, conservation of habitats and species, and consideration of ecological and hydro-morphological processes in river systems. Its implementation involves a cyclical planning process aimed at involving public participation and stakeholder engagement, and achieving and maintaining good water status.

4.3 Environmental Damage

Environmental damage refers to the negative effects on the environment caused by human activities. It encompasses a wide range of impacts, direct or indirect, including pollution of air, water, and soil, deforestation, habitat destruction, loss of biodiversity, and more. These damages can have significant consequences for ecosystems, wildlife, human health, climate change resilience and the overall sustainability of the planet.

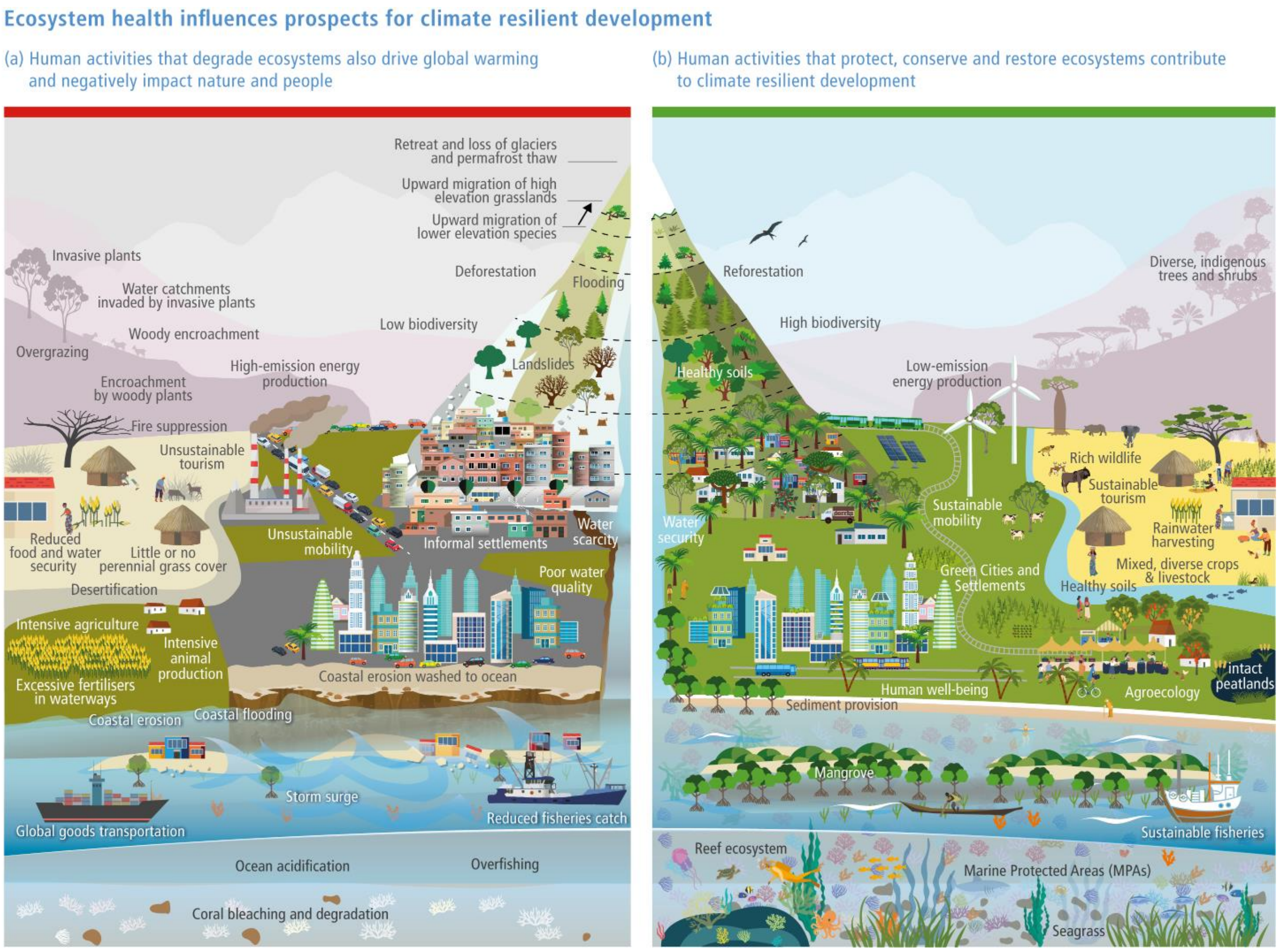


Figure 23. Ecosystems, human activities, and climate resilience

As outlined in last paragraphs, due to the interconnection between climate change and ecosystems it is necessary to protect them, also and mostly, from human activities. Although, industrial activities and other anthropogenic forces can have a real disruptive impact on ecosystems and so it is crucial to analyse the environmental damage derived from these activities and to start actions to prevent, mitigate, remediate, and resolve the impacts of these activities.

So, assessing and evaluating environmental damage is essential for understanding the scope of the problem, identifying the responsible parties, and implementing appropriate measures for mitigation and restoration. Various methods and approaches are used to evaluate environmental impacts, including environmental impact assessments (EIAs), life cycle assessments (LCAs), ecological footprint analysis, and cost-benefit analysis.

EIAs are a systematic process used to predict and evaluate the potential impacts of proposed projects or activities on the environment. They consider factors such as air and water quality, biodiversity, land use, and socio-economic aspects. The goal is to identify and minimize adverse effects and ensure that development is environmentally compatible and sustainable.

LCA is a comprehensive methodology used to assess the environmental impacts associated with a product, process, or activity throughout its entire life cycle, from raw material extraction to disposal. LCA considers factors such as resource use, energy consumption, emissions, waste generation, and potential environmental damage.

Ecological footprint refers to a measure of the human demand on nature's resources and ecosystems. It quantifies the amount of land and water area required to sustain the consumption patterns and waste generation of a population or activity. Ecological footprint analysis helps in understanding the sustainability of human activities and their impact on natural resources.

In Italy, environmental protection is a significant concern, and the country has established laws and regulations to address environmental damage. The Italian legislation includes several key acts and regulations, such as the Environmental Code (Codice dell'Ambiente), which provides a framework for environmental protection and management.

The Environmental Code incorporates European Union directives, such as the Environmental Impact Assessment Directive (2011/92/EU) and the Habitats Directive (92/43/EEC), into Italian law. These directives require the assessment and management of environmental impacts for certain projects and activities, as well as the protection of habitats and species of conservation importance. [20]

In addition to the Environmental Code, Italy has other specific laws and regulations that address environmental damage in various sectors. For instance, the Water Framework Directive (2000/60/EC) (described earlier) and the Legislative Decree 152/2006 establish measures for the protection and management of water resources, including the prevention and control of water pollution. Furthermore, Italy has implemented legislation to combat air pollution, promote waste management, and preserve natural resources.

The evaluation of environmental compatibility and the valuation of environmental damage are integral to these laws and regulations. They involve assessing the potential environmental impacts of proposed projects, determining the level of compatibility with environmental objectives and standards, and quantifying the damages caused by non-compliance or incidents.

Valuation of environmental damage often involves estimating the costs associated with pollution, habitat destruction, and other negative impacts. These costs can include direct expenses for cleanup and restoration, as well as indirect costs related to health impacts, loss of ecosystem services, and impacts on tourism or economic activities.

In Italy, several methodologies and guidelines have been developed to assess and value environmental damage. These include approaches for economic evaluation, such as the estimation of environmental costs and benefits, as well as ecological assessment methods that consider the ecological value of habitats, species, and ecosystem services.

As regards pollution, this term refers to the introduction of harmful substances or contaminants into the environment, resulting in adverse effects on ecosystems, human health, or the quality of air, water, and soil. It can occur from various sources, including industrial processes, transportation, agriculture, and waste disposal. Pollution can manifest in different forms, such as air pollution, water pollution, soil contamination, and noise pollution.

To address and manage pollution, environmental quality standards and emission standards are established. These standards serve as guidelines and benchmarks for acceptable levels of pollutants in the environment. They aim to protect human health, preserve ecosystems, and maintain a sustainable environment.

Environmental Quality Standards (EQS) define the maximum allowable concentrations or levels of pollutants in environmental media, such as air, water, and soil. These standards are based on scientific research and consider the potential risks posed by different pollutants. EQS help regulate pollution levels and ensure that the environment meets certain quality criteria. They are often legally binding and enforced by environmental regulatory agencies.

For example, in the context of air pollution, EQS may set limits for pollutants such as particulate matter, sulfur dioxide, nitrogen oxides, ozone, and volatile organic compounds. These standards define the acceptable concentrations or levels of these pollutants in the ambient air to protect human health and prevent environmental degradation.

Emission Standards, on the other hand, establish the maximum allowable levels of pollutants that can be emitted into the environment from specific sources, such as industries, vehicles, or power plants. Emission standards are designed to control and reduce pollution at its source. They specify the technologies, equipment, or control measures that need to be implemented to limit pollutant emissions.

Emission standards are often established by regulatory authorities and enforced through permits, inspections, and compliance monitoring. They encourage industries and other pollution sources to adopt cleaner technologies, practices, and management strategies to minimize their environmental footprint.

Both environmental quality standards and emission standards play vital roles in pollution control and environmental management. They provide a framework for setting targets, regulating pollution sources, and assessing compliance. By ensuring that pollutants are kept within acceptable limits, these standards contribute to the protection and preservation of the environment and the well-being of both ecosystems and human populations.

Interpreting a standard involves assessing and understanding the results and findings of various studies conducted in epidemiology and toxicology. These studies provide valuable insights into the effects of pollutants or substances on human health and the environment. Interpreting these studies requires considering specific parameters and evaluating the strength of the evidence presented [20].

1. Epidemiologic Study Interpretation: Epidemiologic studies investigate the distribution and determinants of health-related events, such as disease incidence or mortality, within a population. They help assess the association between exposure to certain factors, including pollutants, and health outcomes. When interpreting epidemiologic studies in the context of a standard, the following parameters are often considered:

• Study Design: The design of the study, whether it's a cohort study, case-control study, cross-sectional study, or others, helps determine the strength of the evidence. Cohort and case-control studies are commonly used to establish cause-and-effect relationships between exposures and health outcomes.

• Exposure Assessment: The accurate measurement and characterization of exposure to pollutants is crucial. Exposure assessment methods used in epidemiologic studies include personal monitoring, biomarkers, questionnaires, and environmental modelling.

• Outcome Assessment: The outcome of interest, such as disease incidence or mortality, is assessed to determine its association with the exposure of interest. The assessment may involve clinical diagnoses, medical records, or self-reporting by participants.

• Statistical Analysis: The statistical methods employed, such as relative risk, odds ratio, or hazard ratio, help quantify the association between exposure and outcome. The interpretation involves considering the magnitude of the effect and the statistical significance of the findings.

2. Toxicologic Study Interpretation: Toxicologic studies focus on the effects of substances on living organisms, including humans, and help determine the potential hazards and risks associated with exposure to pollutants. When interpreting toxicologic studies in relation to a standard, the following parameters are often considered:

• Study Design: The study design, such as in vivo (animal) or in vitro (cell-based) experiments, helps assess the relevance and applicability of the findings to human health.

- Dose-Response Relationship: Toxicologic studies evaluate the relationship between the dose of the substance and the response or effect observed. Interpreting the dose-response relationship helps determine the level at which adverse effects may occur.

- Mechanisms of Action: Understanding the underlying biological or toxicological mechanisms by which a substance produces its effects is important. It helps identify potential modes of action and assess the relevance of the findings to human exposure scenarios.

- Exposure Assessment: The interpretation of toxicologic studies also involves considering the relevance of the exposure levels used in the study to real-world exposure scenarios. This helps determine the potential risks to humans at different exposure levels.

- Statistical Analysis: Similar to epidemiologic studies, toxicologic studies employ statistical methods to analyse the data and quantify the strength of the association between exposure and response.

Interpreting epidemiologic and toxicologic studies requires considering the study design, exposure and outcome assessment methods, statistical analyses, and understanding the specific parameters relevant to the study type. By critically evaluating these factors, researchers and regulatory bodies can assess the potential risks associated with pollutants or substances and establish appropriate standards to protect human health and the environment.

In the context of pollution and human health, various parameters are involved in assessing the potential risks and impacts of pollutants. These parameters help in understanding the dose-response relationship, setting acceptable exposure limits, and ensuring the protection of human health. Some of these crucial parameters are [20]:

1. Dose-Effect Curve: A dose-effect curve illustrates the relationship between the dose or level of exposure to a pollutant and the resulting biological response or effect on human health. It helps determine the magnitude and nature of the response at different exposure levels. Dose-effect curves can be used to establish thresholds, identify no observed adverse effect levels (NOAELs), and assess the potential risks associated with specific pollutant exposures.
2. Acceptable Daily Intake (ADI): ADI is an estimate of the amount of a pollutant that can be ingested daily over a lifetime without appreciable health risks. It is derived from toxicological studies and represents a level of exposure considered safe for human consumption. ADI values are typically expressed in milligrams of the pollutant per kilogram of body weight per day (mg/kg/day). ADI helps guide the establishment of regulatory limits and safety standards for pollutants in food and drinking water.
3. Reference Dose (RfD): RfD is a similar concept to ADI but is primarily used for assessing non-cancer health risks associated with exposure to pollutants. RfD represents the amount of a pollutant that can be ingested or inhaled daily over a lifetime without significant adverse effects. RfD values are

expressed in the same manner as ADI, as milligrams of pollutant per kilogram of body weight per day (mg/kg/day).

4. Reference Concentration (RfC): RfC is similar to RfD but focuses on the inhalation exposure pathway. It represents the concentration of a pollutant in the air that can be continuously inhaled without adverse health effects over a lifetime. RfC values are typically expressed in micrograms per cubic meter ($\mu g/m^3$) or parts per million (ppm).
5. Threshold Limit Value (TLV): TLV is a term commonly used in occupational health and safety to represent the level of exposure to airborne pollutants that workers can be exposed to without experiencing adverse health effects. TLVs are established by organizations such as the American Conference of Governmental Industrial Hygienists (ACGIH) and are typically expressed in terms of time-weighted average (TWA) concentrations over an 8-hour workday.

In the context of water pollution, several other parameters and calculations are relevant for assessing and managing risks [19]:

1. Point of Exposure: The point of exposure refers to the specific location where individuals or ecosystems come into contact with contaminated water. It can be a drinking water intake, recreational water body, or an area where aquatic organisms reside. Identifying the point of exposure is crucial for understanding the potential risks and determining appropriate mitigation measures.

2. Natural Attenuation Factor: Natural attenuation is the process by which pollutants in water are naturally reduced or degraded over time through physical, chemical, and biological processes. The natural attenuation factor represents the rate at which pollutants decrease or degrade in the environment. It is an important parameter for assessing the potential for self-cleansing of contaminated water bodies.

3. Bioaccumulation Factor (BAF): Bioaccumulation is the process by which pollutants are taken up and stored in the tissues of organisms. The bioaccumulation factor (BAF) represents the ratio of the concentration of a pollutant in an organism to its concentration in the surrounding water. BAF helps assess the potential for pollutants to accumulate in the food chain and pose risks to higher trophic levels.

4. Biochemical Oxygen Demand (BOD): BOD is a measure of the amount of dissolved oxygen consumed by microorganisms during the decomposition of organic matter in water. It is used as an indicator of organic pollution or the presence of biodegradable pollutants. BOD can be measured in the laboratory, and high BOD levels indicate poor water quality and the potential for oxygen depletion in aquatic systems.

5. Total Maximum Daily Load (TMDL): TMDL is a regulatory term used to represent the maximum amount of a pollutant that a water body can receive while still meeting water quality standards. TMDL calculations consider various factors such as pollutant sources, transport mechanisms, and the assimilative capacity of the receiving water body. TMDLs help guide pollution control strategies and watershed management plans.

6. Risk Assessment: Risk assessment involves quantifying the potential risks associated with exposure to water pollutants. It considers factors such as the toxicity of the pollutant, exposure pathways (e.g., ingestion, dermal contact), and the vulnerability of the exposed population or ecosystems. Risk assessment may involve the calculation of hazard quotients, cancer risks, or other metrics to estimate the likelihood of adverse effects.

These parameters and calculations are used to evaluate and manage water pollution, assess risks, and develop appropriate control measures. They provide insights into the fate and transport of pollutants, the potential for exposure, and the overall impact on water quality and ecosystems. By considering these parameters, stakeholders can make informed decisions to protect and restore water resources.

When evaluating environmental compatibility, various approaches are used to assess the impacts and costs associated with activities that may have environmental consequences. One such approach is the ExternE (External Costs of Energy) procedure, which is a widely recognized method for quantifying the external costs of energy production and consumption.

The ExternE procedure is a comprehensive framework developed by the European Commission to estimate the external costs of different energy-related activities. It considers various environmental impacts, such as air pollution, climate change, noise pollution, and accidents. The procedure assigns monetary values to these impacts to reflect their social costs, which include health effects, ecosystem damage, property damage, and other socio-economic consequences.

On the other hand, social cost-benefit analysis (SCBA) is an economic tool used to assess the social and economic impacts of policies, projects, or activities. It involves the quantification and monetization of both costs and benefits, including environmental and social factors. SCBA aims to determine whether the overall benefits of a proposed action outweigh the costs and provides a framework for comparing different options and selecting the most socially beneficial approach.

Cost-Effectiveness Analysis (CEA): Cost-effectiveness analysis is a method used to compare the costs of different approaches or interventions to achieve a specific environmental objective. It assesses the costs required to achieve a particular outcome, such as reducing pollution levels or improving environmental quality. CEA helps identify the most cost-effective strategies to achieve desired environmental outcomes.

Shadow pricing is an other technique used to assign economic values to environmental goods and services that are not typically priced in the market. It involves estimating the economic value of ecosystem services, such as clean air, clean water, and biodiversity, based on their importance to human well-being and the costs associated with their degradation or loss. Shadow pricing helps capture the environmental compatibility and social costs of activities by incorporating the value of natural resources and ecosystem services into decision-making.

In the context of economic valuation and evaluation of environmental damage, there are various concepts and approaches used in Italian legislation. For example, direct costs are the immediate economic expenses incurred as a result of environmental damage. These costs can include the costs of clean-up, remediation, and restoration activities, as well as the costs of repairing or replacing damaged infrastructure. Direct costs are typically quantifiable and measurable in monetary terms. On the other hand, indirect costs are the economic consequences that arise as a result of environmental damage but are not immediately apparent or directly incurred. These costs are often more difficult to quantify and include factors such as loss of ecosystem services, impacts on human health, and long-term economic implications. Indirect costs may include reduced agricultural productivity, health care expenses, and decreased tourism revenues.

Other economic valuation methods of environmental damage are [20]:

1. Market-Based Methods: These methods rely on market transactions and prices to estimate the economic value of environmental resources. They include:
   - Market Price Method: This approach uses observed market prices of goods and services directly related to the environment. For example, the price of timber or fish can be used to estimate the economic value of forest or aquatic ecosystems.
   - Replacement Cost Method: It estimates the value of an environmental resource by assessing the cost of replacing or restoring it. For instance, the cost of constructing and maintaining a water treatment plant can represent the value of clean water.
   - Avoided Cost Method: This method calculates the economic value by considering the costs that would be incurred if the environmental resource were not available. For instance, the cost savings associated with using natural wetlands for flood control instead of constructing artificial flood control infrastructure.
2. Travel Cost Method: This approach estimates the economic value of recreational or natural resources by analyzing travel expenses related to visiting those resources. It considers factors such as transportation costs, entry fees, and time spent on travel. The method captures the consumer surplus derived from recreational activities.
3. Contingent Valuation Method (CVM): CVM directly asks individuals about their willingness to pay (WTP) or willingness to accept (WTA) compensation for a particular environmental good or service. Surveys are conducted, and responses are used to estimate the economic value. CVM is often used to value non-market goods and services or to estimate non-use values, such as existence value or bequest value.
4. Production Function Method: This method assesses the economic value of an environmental resource by examining its contribution to economic production or the functioning of an ecosystem. It quantifies the relationship between inputs, outputs, and environmental variables to estimate the economic value generated.
5. Damage Cost Assessment Method: This method calculates the economic costs associated with environmental damage. It considers factors such as health impacts, property damage, and loss of ecosystem services. The method estimates the costs of environmental degradation and the economic benefits of avoiding or mitigating that damage.

6. Benefit Transfer Method: This method involves transferring economic values from existing studies conducted in similar contexts to estimate the value of a similar environmental resource. It relies on the assumption that values estimated in one location or time period can be applied to another location or time period with similar characteristics.
7. Damage Cost Avoidance Method: This approach estimates the economic value by assessing the costs avoided through preventive measures that mitigate environmental damage. It quantifies the potential costs that would have been incurred in the absence of such measures.
8. Replacement Cost Restoration Method: This method estimates the economic value by evaluating the cost of restoring or replacing an environmental resource to its original state. It considers the expenses associated with rehabilitation, reclamation, or ecosystem restoration activities.
9. Choice Experiment Method: This method presents individuals with hypothetical scenarios and asks them to make choices that involve trade-offs between different attributes or levels of an environmental resource. The responses are used to estimate the economic value placed on specific environmental attributes.

All these methods rely on basic concepts related to economic value, such as [20]:

1. Cost or Production Value: The cost or production value refers to the economic value of environmental resources based on the cost of producing or extracting them. It includes the expenses incurred in the extraction, processing, and transportation of natural resources. This value is typically used in industries that rely on natural resource extraction, such as mining or forestry, to assess the profitability of their operations.

2. Market or Capitalization Value: Market or capitalization value represents the economic value of an environmental resource based on its market price or the capitalized income it generates. It considers the value assigned by the market to the resource, taking into account factors such as supply and demand dynamics, market conditions, and potential future earnings. This value is often used for ecosystem services with established markets, such as timber sales or carbon credits.

3. Subrogation Value: Subrogation value refers to the economic value assigned to the restoration or replacement of a damaged environmental resource. It represents the cost required to restore the resource to its pre-damage condition or to replace it with an equivalent resource. Subrogation value is particularly relevant in legal contexts where compensation or restitution for environmental damage is sought.

4. Complementary Value: Complementary value refers to the economic value of environmental resources that are essential for the functioning and support of other economic activities. It recognizes that certain environmental resources provide services or inputs that are crucial for various sectors of the economy. For example, wetlands that provide water filtration and flood regulation services have a complementary value for water supply and flood control activities.

5. Opportunity Cost Criterion: The opportunity cost criterion assesses the economic value of an environmental resource based on the value of the next best alternative forgone or foregone opportunity. It reflects the benefits that could have been gained from using the resource for an alternative purpose. The opportunity cost criterion is often used to evaluate trade-offs and prioritize different uses of environmental resources.

These concepts play a role in economic valuation and decision-making processes related to environmental resources and damage. They help in understanding the economic significance of environmental assets, the costs associated with environmental damage, and the trade-offs between different uses and management options.

5. Case study: Cengio and Saliceto Site of National Interest

5.1 Bormida River and its ecosystem

The Bormida Valley, located in the hydrographic basin of the Bormida River, is an Alpine-Apennine valley. It extends from the Ligurian Alps, entering the Ligurian Apennines, in Savona, and then continues in Piedmont between Monferrato and the high Langhe, until it reaches the Po Valley where the Bormida River merges with the Tanaro (east of Alessandria). The Bormida River, approximately 160 kilometers, is the main watercourses in the area and ends its course into the Ligurian Sea [21].

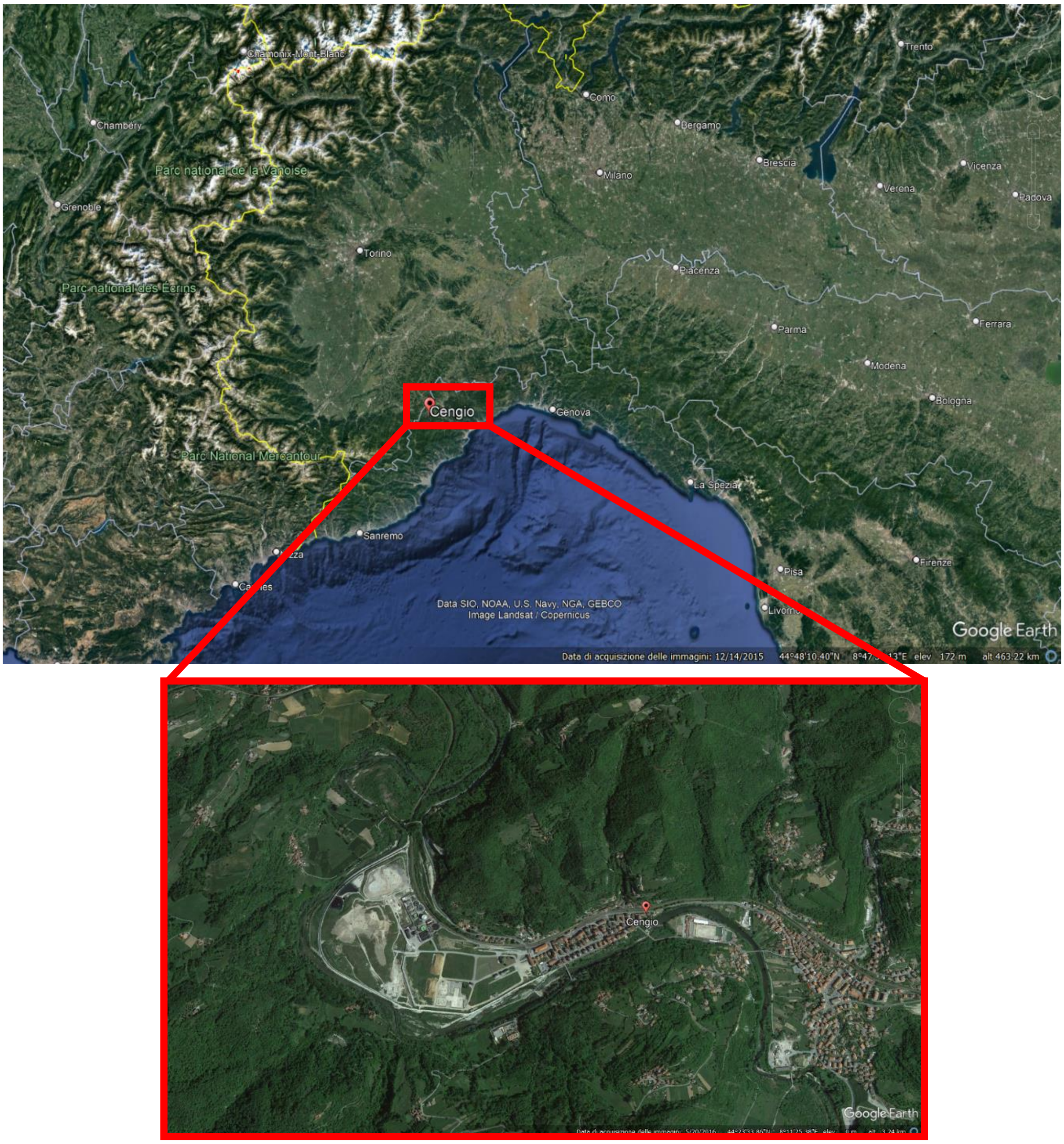


Figure 24. Site of Cengio in North Italy

The Bormida Valley is home to many species of wildlife, including wild boars, foxes, badgers, weasels, martens, hares, roe deer, red deer, and wolves. In the wooded areas, various species of birds can be observed, such as the green woodpecker, cuckoo, pheasant, blackbird, and magpie. The vegetation of the valley mainly consists of oak and chestnut forests, but there are also many other plant species, such as hazelnuts and beeches, maritime pine and laurel, and numerous species of herbaceous plants. [23] [24] [25] [26]

Furthermore, the Bormida Valley is an area of great natural interest, to the extent that many areas have been declared Sites of Community Importance (SCI) or Special Protection Areas (SPA) under the European Union's Habitat Directive and Birds Directive. These areas are protected and managed to preserve the ecosystem and biodiversity of the area. The Bormida Valley and the Bormida River represent an important natural ecosystem, rich in biodiversity and animal and plant species. [26] [27]

The area of Cengio is located within the Bormida Valley, in the province of Savona, and is crossed by the Bormida River. It is characterized by a varied vegetation and a rich fauna. In the area, numerous plant species can be found, including chestnut trees, beeches, oaks, maples, hornbeams, and turkey oaks. The area is also rich in meadows and pastures, where a wide variety of flowers and herbaceous plants can be found. [23] [24][25]

In terms of the economy, Cengio is primarily based on agriculture and small-scale industries. The fertile land surrounding the town is well-suited for cultivation, making agriculture a crucial economic activity. The region produces various crops such as cereals, fruits, legumes, vegetables, and olive oil. Vineyards are also prevalent, contributing to the production of high-quality wines, including the renowned Ligurian Rossese and the so called "Dolcetto". [22]

The agricultural sector plays a vital role in the local economy, providing employment opportunities and contributing to the overall prosperity of the community. Traditional farming practices are often upheld, with an emphasis on sustainable and organic methods, aligning with the growing demand for locally sourced and environmentally friendly products.

Cengio's proximity to the Bormida River greatly influences its economy, culture, and social fabric. The river serves as an essential water source for irrigation, supporting agricultural activities in the region. The fertile soils along the riverbanks owe much to the sediment carried by the Bormida, enhancing the productivity of the agricultural sector.

Furthermore, the Bormida River has historical and cultural significance. Its presence has shaped the development of settlements and trade routes throughout the region over centuries. The river's influence is visible in local traditions, folklore, and cultural events that celebrate the connection between the community and its natural surroundings.

From an environmental standpoint, the Bormida River and its surrounding ecosystem harbour a rich biodiversity. The river's flow supports diverse flora and fauna, contributing to the overall ecological balance of the area. Efforts are made to preserve the river's cleanliness and protect the surrounding natural habitats, ensuring a sustainable environment for future generations.

The Bormida River supports a variety of aquatic plant species. These can include submerged plants like waterweed (Elodea) and pondweed (Potamogeton), as well as emergent plants such as reeds (Phragmites) and water lilies (Nymphaea). Aquatic plants contribute to the overall ecosystem health by providing oxygen, shelter, and food for various organisms, as well as stabilizing sediments and enhancing water quality. [23][24][25]

A diverse range of fish species are present in the Bormida River, including common species like trout (Salmo trutta), chub (Squalius spp.), and barbel (Barbus spp.), la trota marmorata (Salmo trutta marmoratus) e il cavedano (Leuciscus cephalus). These fish species rely on the river for breeding, feeding, and shelter. The river ecosystem also supports a variety of invertebrates such as insects, crustaceans, mollusks, and worms, which form an essential part of the aquatic food web. [28] [31]

The ecosystem includes wetlands and floodplains adjacent to the river. These areas are periodically flooded and provide important habitats for a variety of plant and animal species. Wetlands and floodplains serve as breeding grounds, foraging areas, and refuge for wildlife. They also play a crucial role in water purification, nutrient cycling, and flood mitigation.

A lot of bird species are attracted by the Bormida River ecosystem, both resident and migratory. Birds rely on the river and its associated habitats for nesting, feeding, and resting. Species such as herons, kingfishers, ducks, and various waders can be found along the Bormida River, making it an important area for birdwatching and bird conservation.

The relationship between Cengio and the Bormida River extends beyond economics and environment. The river acts as a social and recreational hub, providing opportunities for fishing, boating, and other water-based activities. Its picturesque landscapes and scenic beauty also attract tourists, fostering cultural exchange and promoting local tourism, which, in turn, stimulates the local economy. [22]

The ACNA company, active in the production of chemical products for over a century, has had negative repercussions on the environment in the Cengio area, with consequences for the Bormida River and the surrounding valley, which will be analysed in detail later. The company's activities have resulted in the release of pollutants into the air, soil, and water of the river, causing significant environmental damage.

At the beginning of the 20th century, before the company's activities began, the valley was full of life, and the waters were inhabited by frogs, moray eels, barbels, eels, shrimps, otters, wild ducks, and other native animal species. [22]

The repercussions on the ecosystem of the river and the valley have been numerous. In particular, water and soil pollution has been recorded, resulting in damage to the flora and fauna of the area. Loss of biodiversity has occurred, with the disappearance of certain animal and plant species, causing serious harm to the ecosystem of the Bormida River area and the surrounding valley.

Regarding fauna, the disappearance of many fish species, such as brown trout (Salmo trutta), marble trout (Salmo trutta marmoratus), and chub (Leuciscus cephalus), has been observed. Furthermore, reductions in bird populations, such as magpies (Pica pica) and green woodpeckers (Picus viridis), have also been reported. While no cases of extinction have been reported for terrestrial species, the presence and distribution of some mammal species, such as foxes and otters, have been negatively affected by water and soil pollution. [22][23][25]

In terms of flora, significant damage to native plants has been reported, including the disappearance of species like the orchid (Orchis mascula) and woundwort (Stachys recta). [22]

After the closure of the ACNA company, various activities have been carried out by ENI company to remediate and restore the health of the ecosystem in the Cengio area. These activities have been promoted by local and national authorities, in collaboration with environmental organizations and local communities.

The actions implemented for the remediation and recovery of the ecosystem in the Cengio area have been diverse. In particular, monitoring and analysis of water, soil, and air quality have been conducted to assess the extent of the environmental damage and plan remediation activities.

Efforts have also been made to restore flora and fauna, including the reintroduction of certain animal and plant species and the creation of protected areas. Soil remediation activities have been carried out, involving the removal of pollutants and the restoration of the natural characteristics of the land.

After the remediation and environmental recovery interventions carried out by ENI in the Cengio area, significant improvements have been observed in the health of the ecosystem, habitat, and local biodiversity. Also, some animal and plant species that had disappeared or were in steep decline have returned or shown population growth.

In summary, ACNA's century-long activity in Cengio has caused significant environmental damage to the river and valley area, impacting the health of citizens, agricultural activities, and the social structure. However, thanks to the remediation and environmental recovery efforts implemented by ENI, the environmental impact has been reduced, and the health of the ecosystem in the area has been restored. Monitoring and remediation activities will continue to ensure the protection and conservation of the area's environment.

5.2 Chronology of the events

Over the years, the ACNA industrial site located in Cengio has undergone gradual expansion, resulting in its current size of around 55 hectares. Adjacent to the perimeter wall, there exist two distinct areas along with the Pian Rocchetta landfill, which serves as a dividing point between the regions of Liguria and Piedmont, specifically within the municipalities of Cengio and Saliceto.

In 1882, the facility was originally established as an explosives factory, under the name of SIPE in 1910. However, following World War I, it underwent a transformation and was converted into a factory specializing in the production of organic intermediates. These intermediates were primarily utilized in the dye and pigment industry. Consequently, in 1912, the facility's name was changed to ACNA, Azienda Coloranti Nazionali ed Affini

In 1928 the ACNA S.P.A was established, starting the production facilities in Cengio. Montecatini group acquired the company after the bankrupt of 1931, employing about 700 people at the time.

The detrimental impact of pollution discharges into the river became evident as early as 1909, when the initial signs of contamination were reported. Consequently, in 1922, the Magistrate of Mondovì issued an ordinance declaring the drinking water wells of the Cortemilia aqueduct in Cuneo unusable due to contamination, highlighting the severity of the situation. In the first 30 years of the company's operation, the colour of the Bormida River completely changed in the surrounding areas, and dead fish began to appear on the surface.

In 1938, ACNA faced a lawsuit filed by farmers from the Bormida Valley in Millesimo due to damages caused to their agricultural practices. The farmers initiated an agricultural revolt against the company, as the water from the river had become unsuitable for irrigation purposes. However, despite the farmers' claims, the Genoa Hydrographic Service did not acknowledge the extent of the damage caused and concluded in 1959 that, although polluted, the river water did not result in significant harm to agricultural activities.

In 1960, the Ministry of Public Works granted ACNA the renewal of permission to utilize the waters of the Bormida River for industrial operations, extending the validity of this permission to 70 years. Subsequently, in 1964, the Interministerial Commission for the Study of the Val Bormida problem was established. This commission, responsible for addressing the issues related to the Bormida Valley, was later succeeded by the Commission for the Protection of Soils from Pollution. During this time, Montecatini became Montedison.

In 1976, the Mayor of Acqui Terme filed a complaint against unknown persons for "negligent poisoning of water intended for human consumption." At that time, 1,500 people were employed by ACNA.

In 1982, the provincial administration of Asti and eight municipalities located in the Bormida Valley initiated legal proceedings against ACNA, seeking compensation for the damages caused by the company. The Court of Savona issued a verdict, sentencing four managers of the facility to two years and two months of imprisonment for violating Article 440 of the Penal Code. However, the subsequent Court of Appeals in Genoa overturned the previous conviction and acquitted the managers.

In 1982, the Cengio facility was redefined, transforming itnto a company dedicated to the production and sale of organic intermediates for the global market. In January 1983, A.C.N.A. S.P.A transferred the Cengio facility to ACNA CHIMICA ORGANICA.

Environmental monitoring conducted in the 1980s confirmed the severe pollution in the water environment, leading the Liguria and Piedmont regions to jointly request the declaration of the Bormida di Millesimo River as an area of high environmental risk under Article 7 of Law No. 349/1986. This declaration was made in 1987, and ACNA was identified as the main polluter. [33]

In the summer of 1988, a large toxic cloud emerged from the ACNA facility in Cengio, which quickly spread to several municipalities on the border between Liguria and Piedmont. This incident led to intoxications and raised significant concerns among the population. The release of toxic gases was just the latest in a series of accidents and environmental damages caused by ACNA, which sparked a major protest involving over 8,000 people. In this case as well, the trade unions sided with the company, believing that the priority should be to protect jobs. [34]

Incidente all'Acna di Cengio mentre a Roma si decide sulla chiusura

Allarme, un'altra nube tossica

Divisi i ministri: Ruffolo (Ambiente) favorevole al blocco, Battaglia (Industria) più cauto - Cortei pro e contro anche nei centri della Val Bormida - La Montedison: «Non c'è stato pericolo»

Il costo della sicurezza

ROMA — C'è un altro fronte, dopo quello della Farmoplant di Massa, nel rischio ambiente. Un'altra nube tossica, questa volta all'Acna di Cengio, anch'essa della Montedison. Ieri mattina, all'indomani dell'annunciata decisione del ministro dell'Ambiente Ruffolo di chiudere per sei mesi la fabbrica di coloranti, una fuga di anidride solforosa è venuta a drammatizzare la situazione.

[...] mente entro i limiti previsti dalla legge Merli». Di qui la cautela di Battaglia, che prendeva tempo.

Ma intanto l'incidente accendeva tensione e paura nella Val Bormida. La nube di anidride solforosa si stendeva verso i paesi vicini, situati in Piemonte, da sempre contrari alla presenza dell'Acna di Cengio, che si trova appena al di là del confine, in Liguria. [...]

Figure 25. "La Stampa" - 24 luglio 1988

During the same year, ACNA faced its most significant crisis and was handed over to the newly formed Enimont. Enimont was an ambitious joint venture established between Montedison and ENI; however, it proved unsuccessful and eventually collapsed in 1991. ENI maintained control of ACNA through its subsidiary EniChem. This transfer of control shed light on the substantial constraints faced by ACNA, as the company was experiencing significant financial losses, amounting to around 80 billion lire annually (equivalent to approximately 90 million euros in today's currency).

The activities of ACNA were split, in 1994, liquidating ACNA Chimica Organica, and the newly formed Organic Chemicals s.r.l. taking over the management of the remaining operational plants.

ACNA permanently closed in January 1999, resulting in 200 employees being put on temporary layoff.

In May of the same year, a state of socio-environmental emergency was declared by the Presidency of the Council of Ministers. With the decree n. 2986 in May 1999, titled "Urgent Measures to Address the Emergency Situation Arising from the Environmental Crisis in the Area of the Industrial Site of ACNA, located in the Municipalities of Cengio, Savona Province, and Saliceto, Cuneo Province, and the Bormida River," Dr. Stefano Leoni was appointed as Commissioner to address the emergency situation caused by the presence of contaminated waste, including hazardous waste, stored on the site. The estimate is three million cubic meters of pollutants, along with an additional 300,000 cubic meters of effluents stored in lagoons, for which ACNA had requested the construction of an incinerator. [33]

In the meantime, in December 1998, Law No. 426 included the area in the first list of National Sites of Interest, allocating 30 billion lire for remediation interventions. Subsequently, the ministerial decree of October 20, 1999, approved its perimeter.

The perimeter identified three zones [33]:

ZONE A, defined as a high-risk area, includes the areas occupied by the industrial settlement, the Pian Rocchetta landfill, and the bed of the Bormida River branch of Millesimo from immediately upstream of the water intake of the ACNA plant in Cengio to the morphological narrowing point of the valley on the river itself, upstream of the town of Saliceto.

ZONE B encompasses the bed of the Bormida River branch of Millesimo from the point immediately following the end of Zone A to the administrative boundary between the municipalities of Monesiglio and Prunetto.

ZONE C includes the bed of the Bormida River branch of Millesimo from the point immediately following the end of Zone B to its confluence with the Spigno branch.

With the decree n. 2986, an additional 20 billion lire, allocated by the Master Plan referred to in Article 7 of Law No. 344 of October 8, 1997, brought the total funding available to the Commissioner to 50 billion lire.

On December 4, 2000, the "Accordo di Programma" was signed between the Minister of the Environment, in agreement with the Ministers of Health and Industry, Trade, and Handicrafts, in consultation with the Presidents of the Liguria and Piedmont regions, the Commissioner, and the representatives of ACNA CO in liquidation and ENICHEM S.p.A. (later SYNDIAL, today ENIRewind, part of the ENI Group). [33]

The Agreement emphasized the importance of conducting remediation activities at the site while ensuring the preservation of environmental and health protection standards. It highlighted the need to facilitate the establishment and operation of sustainable and eco-friendly productive activities and initiatives. As per the Agreement, the liquidated company ACNA CO was required to present a preliminary design within two months, outlining the proposed measures for remediation and safety procedures for both the industrial site and landfill areas. These measures encompassed the removal of waste from the designated areas.

Under the same Agreement, ACNA committed to reduce the volume of water extracted from the Bormida River. Additionally, ACNA pledged to revise its application for the concession of large-scale public water diversion, indicating a willingness to reassess its water usage practices. Furthermore, ACNA agreed to implement all necessary measures aimed at significantly reducing the production of leachate.

In 2002, the first remediation project was presented by Enichem, SYNDIAL (today ENIRewind), which has been ongoing for almost 20 years with subsequent modifications and ongoing updates, which will be discussed in detail in the fourth paragraph.

5.3 Characterization of the site

The site is situated in close proximity to a bend in the Bormida River. Before the establishment of the industrial plant, the river exhibited a morphological structure characterized by multiple tiers of river terraces. However, these terraces were later levelled using backfill material, including residues from industrial processes, to facilitate the construction of production facilities. During the 1920s, the course of the river itself was redirected to create lagoon areas, which were subsequently filled with waste generated from the manufacturing processes. The overall area of the site, including the Pian Rocchetta area, spans approximately 67 hectares, with average elevations standing at around 400 meters above sea level.

From the beginning of site's redevelopment, the site was divided into four zones with homogeneous characteristics to better define the objectives [38]:

- zone A1 (called waste area): located in the western sector of the plant, historically used as a deposit for production residues (material of industrial origin and saline waste accumulation basins);
- zone A2 (industrial area): located in the central and eastern area of the site, characterized by the presence of former production plants and industrial infrastructures and subject to future reuse and reindustrialisation;
- zone A3 ("Aree Golenali"): includes the areas immediately outside the plant on the side of the Bormida River (accumulations of industrial waste);
- zone A4 ("Area Pian Rocchetta"): located in a bend on the right hydrographic side of the Bormida river, about one kilometer west of the industrial settlement, in the Municipality of Saliceto (landfill of industrial R.S.U. residues).

Figure 26. Site zoning

The procedures for drilling and sediment sampling were agreed between ARPA Piemonte, ARPA Liguria, ANPA (now APAT) and the Technical-Scientific Office of the Extraordinary Commissioner for ACNA Reclamation; a " Protocollo per l'esecuzione degli interventi di caratterizzazione nelle aree dello stabilimento ACNA di competenza privata" was then drawn up (26/5/2000). The characterization was divided into two main phases. The first was carried out between 2000 and 2001, the second between 2001 and 2004. [33]

The first characterization, as already anticipated, confirmed the existence of significant and layered contamination throughout the site, necessitating urgent and efficient interventions. Several areas of the facility, particularly the A1 section, which corresponds to the paleo-riverbed of the Bormida River, were filled with industrial waste following the common practices of the early decades of the previous century. This resulted in the formation of a waste layer with a thickness of approximately 30 meters. Furthermore, within the same area, there were 13 lagoon basins that still contained approximately 300,000 cubic meters of saline waste, comprising sodium salts and ammonia.

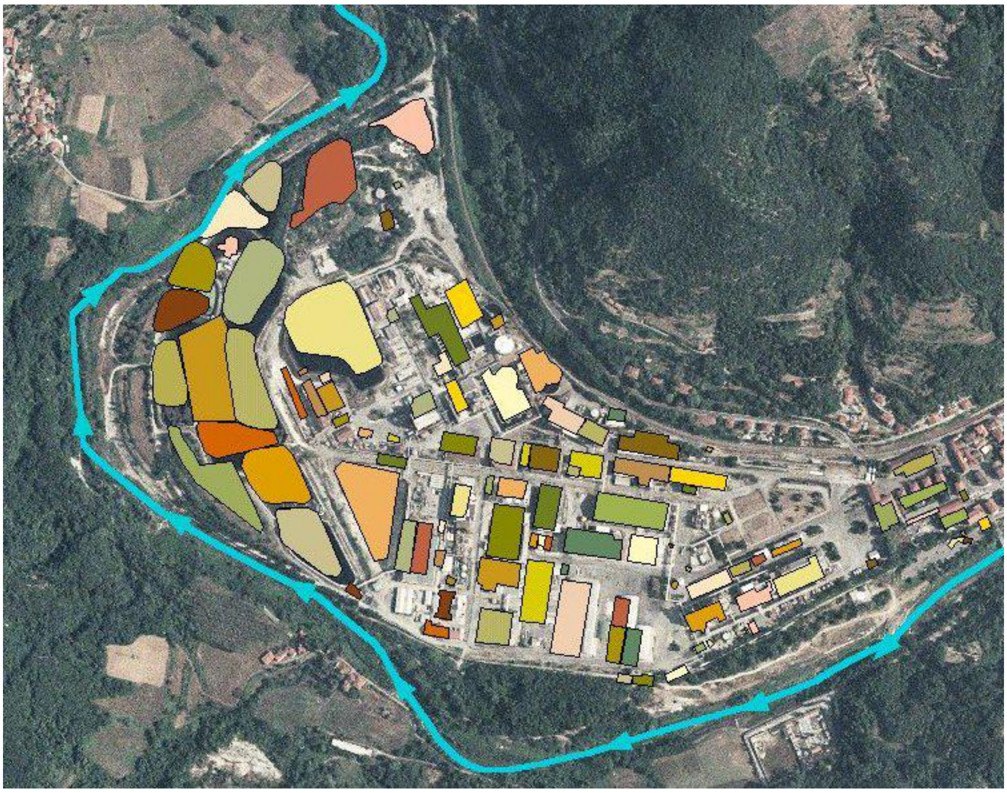


Figure 27. Visualization of lagoon basins and industrial buildings

The situation found in the characterization of the site was about 77 hectares in total, with an influence as regards pollution of over 70 km of valley; 13 lagoon basins with a surface area of approximately 50,000 square meters (of which 8 uncovered and 5 covered); about 4,000,000 cubic meters of waste and contaminated material. Furthermore, evidence of groundwater contamination. [37][38]

Specifically, in zone A1 1,300,000 cubic meters of contaminated waste and soil were found, plus the 300,000 cubic meters of saline waste already mentioned; in zone A2 150,000 cubic meters of contaminants from organic and inorganic compounds; in zone A3 310,000 cubic meters of contaminated land and 200,000 cubic meters of waste; in zone A4 200,000 cubic meters of waste stored [37].

Moreover, other secondary but highly relevant environmental risks have been evaluated, such as the risk of flooding, including for contaminated areas, in this regard there were floods in 1994, in 2016 and a more recent one last October in which fortunately have not occurred significant damage [30][42]; and also risk of percolation and risk of infiltration.

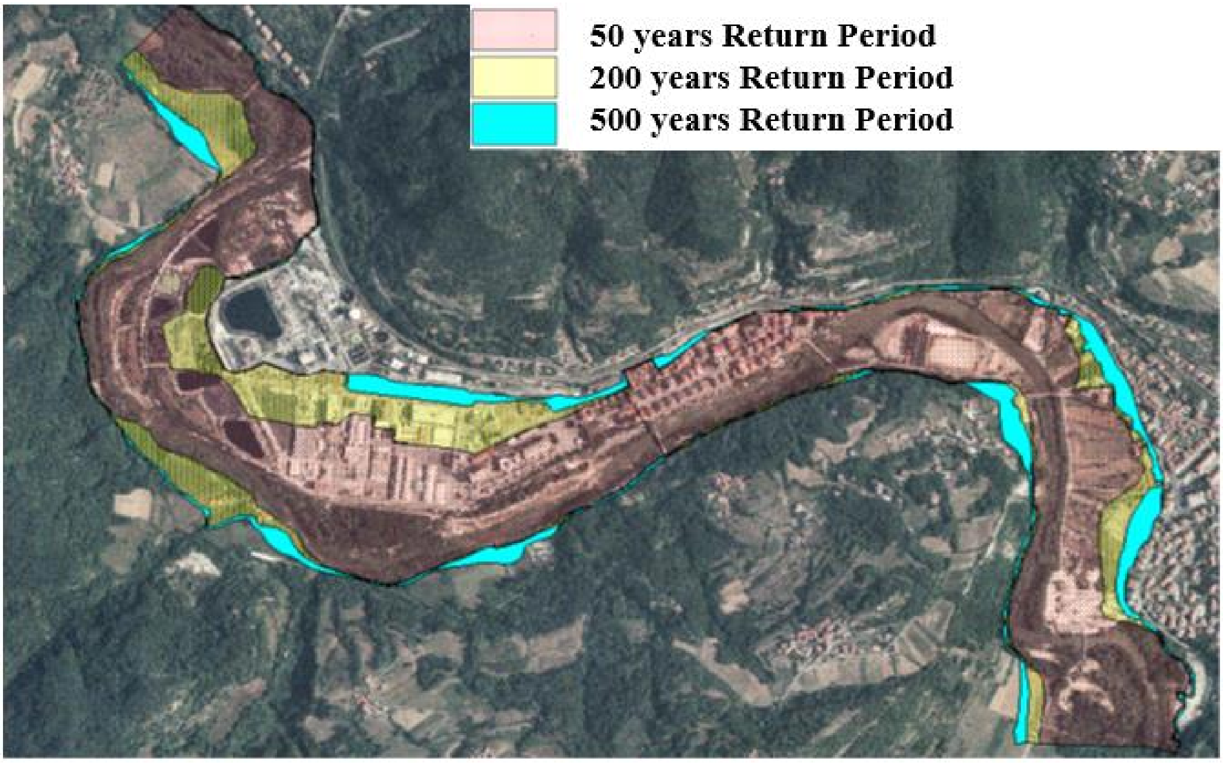


Figure 28. Flood risk map and relative Return periods

Figure 29. Percolation and Infiltration Risk

During the "Accordo di Programma" phase, the characterization plan, which involved studying the soil, subsoil, and water to assess pollution levels, was divided into a first part focused on the external area of the establishment (under public jurisdiction) and a second part encompassed the area within the plant, under Syndial responsibility. This division allowed for a systematic evaluation of the pollution levels in both the external and internal areas of the site.

The analyses on the soil and groundwater matrices envisaged the determination of 262 parameters (including naphthalenesulphonic and anthraquinsulphonic compounds, aromatic amines, nitrobenzenes and chloronitrobenzenes, chlorinated and non-chlorinated phenols, chlorobenzenes, etc.). For many of these parameters, typical of industrial productions, specific limits have been identified by an ANPA-ISS-ARPA Liguria (ARPAL)-ARPA Piemonte (ARPAP) technical table [33] [37].

The analyses were subdivided in this way:

- Soils from boreholes in external areas: 30 boreholes pushed up to bedrock and 5 exploratory wells, 163 samples analyzed
- Lands from areas adjacent to the ACNA perimeter: 15 surveys pushed up to the bedrock, 44 samples analyzed
- Alluvial sediments taken from the riverbed: 20 sediments sampled from the fluvial branch of the Bormida di Millesimo river, 20 samples analyzed

- Alluvial sediments taken outside the riverbed: sampled 30 sediments adjacent to the fluvial branch of the Bormida di Millesimo river, 30 samples analyzed
- Particulate matter in suspension: 5 samples analysed taken from the settler.

Furthermore, a field activity was carried out by ARPAL and ARPAP for the supervision and control of the internal areas on:

- 630 surveys.
- 1900 soil samples for the analysis of volatile compounds.
- 2101 soil samples for the analysis of non-volatile compounds.
- 50 groundwater samples taken in static conditions.
- Monthly piezometric monitoring on 50 piezometers.
- Counter-analysis on 10% of the samples out of 213 analysed

And on the external areas the creation of:

- 60 surveys.
- Monthly piezometric monitoring on 18 piezometers.
- 163 soil samples.
- 72 groundwater samples.
- 24 surface water samples.
- 6 samples of particulate matter in suspension.
- 40 river sediment samples in the riverbed.
- Biomonitoring of the Bormida river.
- 5 continuous monitoring stations for the waters of the Bormida river.

In the first phase, the sampling of the area inside the plant took place with aerial distribution of the survey points according to a very dense regular mesh (25x25 m) and by taking the samples vertically with a stratigraphic criterion, distinguishing, in particular, a deposit deriving from anthropic action, the incoherent deposits of alluvial origin, the level of alteration of the marl-sandstone substrate, and finally the marl-sandstone substrate. Were also made wells or trenches for direct geognostic testing carried out with half an excavator equipped with a backhoe and deepened up to a maximum of 3 meters. Elementary samples were taken from the 4 walls of the wells, scarifying the exposed surface, and subsequently homogenized to form a single sample weighing about 5 kg [33][41].

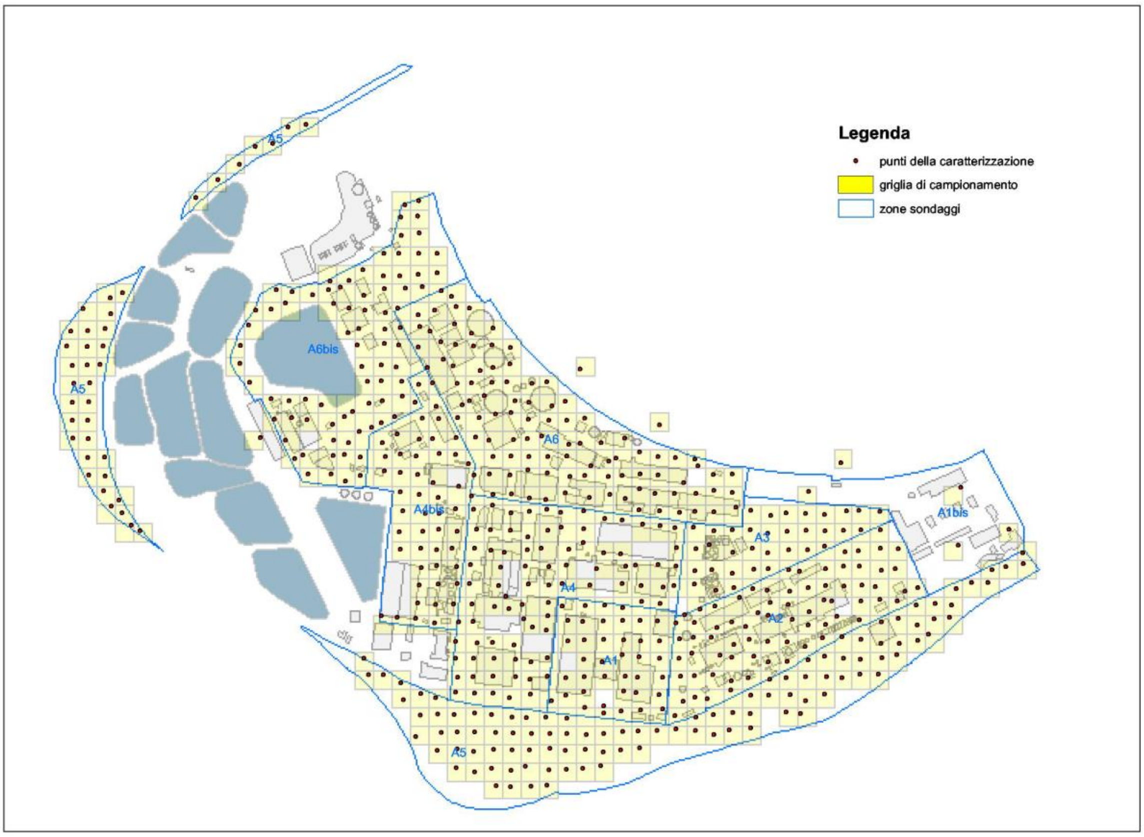


Figure 30. Sampling mesh

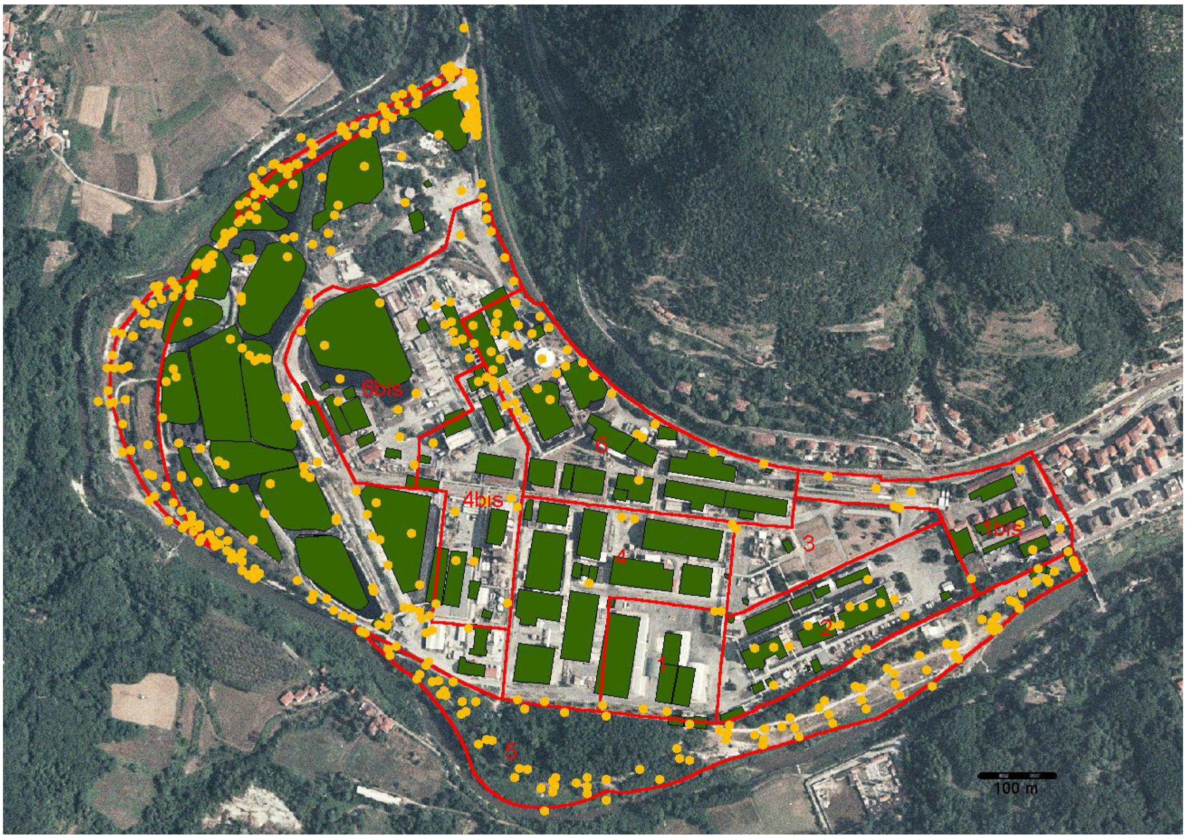


Figure 31. Wells and piezometers

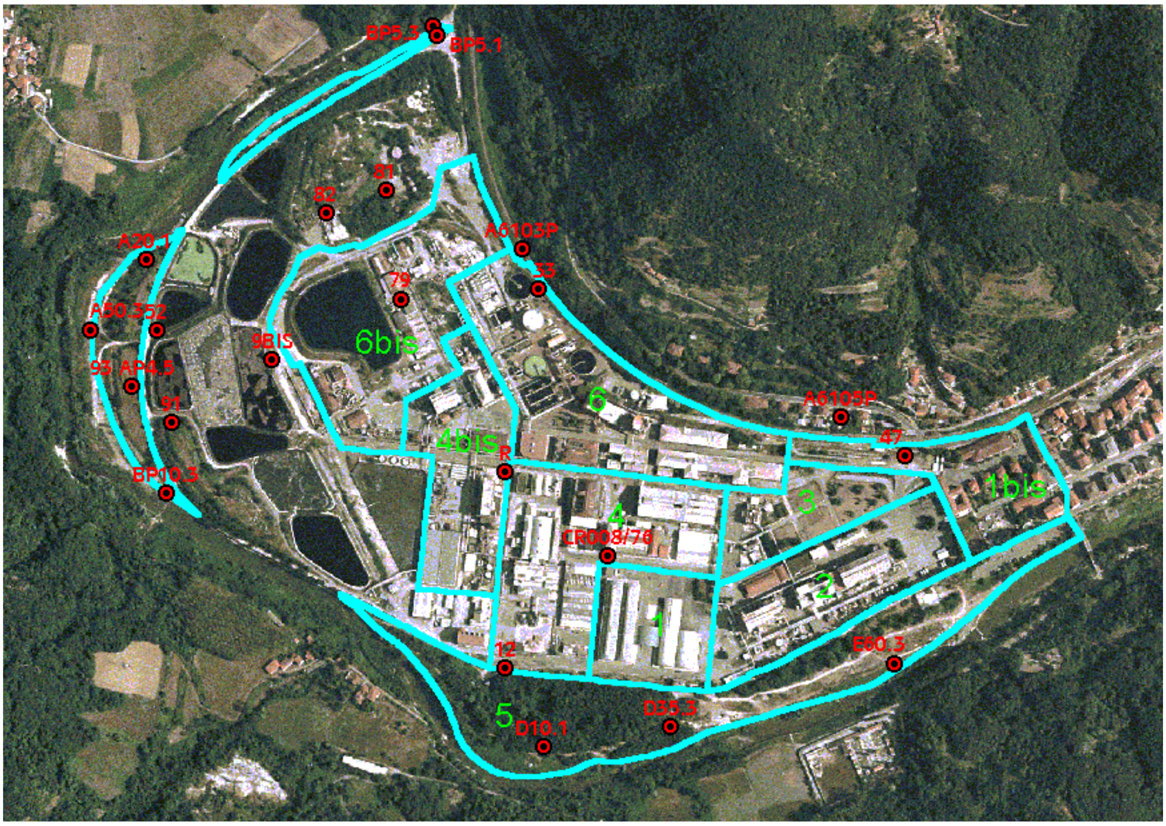


Figure 32. Sampling point for groundwater monitoring

The initial phase of characterization revealed that the soils within the plant area were contaminated with a combination of organic and inorganic pollutants. The concentrations and types of polluting compounds detected in both the waste and soil exhibited anisotropy. Additionally, there was evidence of waste and landfill materials being mixed becoming indistinguishable. These findings underscored the complex and diverse nature of the pollution present within the site's soils.

In particular, regarding soil analysis, it emerged that out of a total of about 2100 samples, over 500 were found to have concentrations above the acceptable limit for at least one pollutant. Furthermore, through the corrections of the analyzes carried out by ARPA, an increase was recorded with respect to the criteria of the ACNA analysis, of 47% for the parameters and of 30% on the samples which resulted above the limit of acceptability [37].

In the external public areas, the characterization was completed and largely conducted directly or under the control of the Regional Agencies, with the same investigation methods followed in the characterization of the private area, according to what is established by the document "Piano di caratterizzazione delle Aree di competenza della Pubblica Amministrazione comprese nelle zone A, B e C perimetrate" approved with the Services Conference held at the Ministry of the Environment on 7 March 2000. The characterization plan as a whole had the task of [33]:

- evaluate whether for the pollutants contained in the sources of contamination still present on the site there were active migration paths capable of reaching the environmental matrices of the Bormida river;

- identify the presence, concentration and distribution of pollutants connected with the previous activities of the ACNA of Cengio, in the surface waters, groundwater, soil and subsoil, alluvial sediments and suspended sediments of the river Bormida of Thousandth;
- collect the necessary and preparatory data for the definition of the definitive conceptual model of the site which allows for the implementation of any safety measures, environmental reclamation and restoration, monitoring of the area in question.

Thus, it emerged that [33]:

• In the floodplain areas outside the site and between the river and the perimeter of the plant, (consisting of landfill including waste disposed of there over the course of a century of activity) conditions for exceeding the regulatory limits for numerous compounds with the presence of semi-volatile substances (such as chlorobenzene) and soluble substances (such as naphthalene sulphonic compounds) probable evidence of a relatively recent origin of the observed pollution.

• For surface waters, irregular trends of contamination with "superi" on metals, phenols and hydrocarbons emerged in zone A (both upstream and downstream of the ACNA discharge), and also in zone B and C. Traces were detected also naphthalene sulphonic compounds (also upstream of the ACNA plant).

• Metal contamination was found in the groundwater, also widespread throughout the valley, in particular as regards Arsenic, Manganese and Iron; presence of high concentrations of organic substances, have been detected in the area of the plant; some organic substances were found to exceed the reference limits in the surrounding areas.

In conclusion, from the analyzes carried out, the picture of the main contaminants present on the site includes, in highly variable concentrations: arsenic, iron, mercury, copper, manganese, lead, zinc, aromatic amines, nitrobenzenes, tetrachlorethylene, tetrachlorobenzene, benzene, chlorobenzene, PAHs, naphthalene, PCBs, phenols, naphthalene sulphonic compounds, halogenated aromatic compounds. [33][35][36][37]

Following the initial phase of characterization, the second phase of investigations aimed to delve deeper into the previously collected information. This involved focusing on areas that exhibited significant criticalities or anomalous conditions. The objective was to intensify data collection in these specific areas to verify and, if necessary, either confirm or reconsider the findings from the first phase of characterization. This phase aimed to provide a more comprehensive understanding of the site's contamination and refine the knowledge acquired during the initial stage of investigations. In this phase, ARPAL carried out analysis in the upper part of the Bormida River basin di Millesimo, in areas not previously investigated and presumably far from significant influences, in order to acquire site-specific reference values ("natural background" values), in particular for some metals.

The supplementary investigations conducted on the surface waters (Bormida River di Millesimo), confirmed the continued significant impact of the ACNA discharge. This was evident from the notable increase in specific electrical conductivity observed as the water flowed from the upstream area to the downstream region of the drain. These findings indicated that the discharge from ACNA still had a considerable influence on the chemical-physical state of the surface waters.

5.4 ENIRewind activities and remediation technologies

The redevelopment plan of the Site of National Interest of Cengio and Saliceto, launched as early as 1988 following the resolution of the Council of Ministers which recognized Val Bormida as an "area ad elevato rischio di crisi ambientale", was consolidated in 2000 with the signing of the "Accordo di Programma" between the former ACNA, the Ministries of the Environment, Industry and Health, the Liguria and Piedmont Regions and the Commissioner Delegate. [40]

In April 2002, Enichem/Syndial/ENIRewind presented the first preliminary reclamation project ("Sito di Cengio Saliceto – Progetto Preliminare di Bonifica") which essentially envisaged [33]:

- Demolition of obsolete industrial buildings
- Making the area called A1 safe and the deposit in this area of contaminated materials from the reclamation activities of the remaining areas.
- Disposal of saline waste contained in the basins located in Zone A1
- The reclamation with safety measures of the remaining area of the plant called A2 by removing the contaminated soils present in the unsaturated zone and, partially, in the saturated zone and placing them in the A1 zone, filling with land compatible with the intended use of the area.
- Reclamation by removal of waste and selective excavation of contaminated soils and fills in the floodplain area called A3 (in almost the entire area the marly layer has been reached) and their embankment in zone A1; remodulation of the area with hydraulic works for regulating the course of the river and construction of an embankment close to the enclosure wall of the plant using suitable materials.
- Reclamation by removing all the waste present in the Pian Rocchetta landfill and depositing it in Zone A1.
- Construction of embankment protection works against hydraulic risk and leachate containment and drainage

The first activities carried out were containment works, consisting of an alternation of masonry, concrete, plastic diaphragms, jet grouting and drainage trenches, in order to prevent the seeping of groundwater from the plant to the outside. [40]

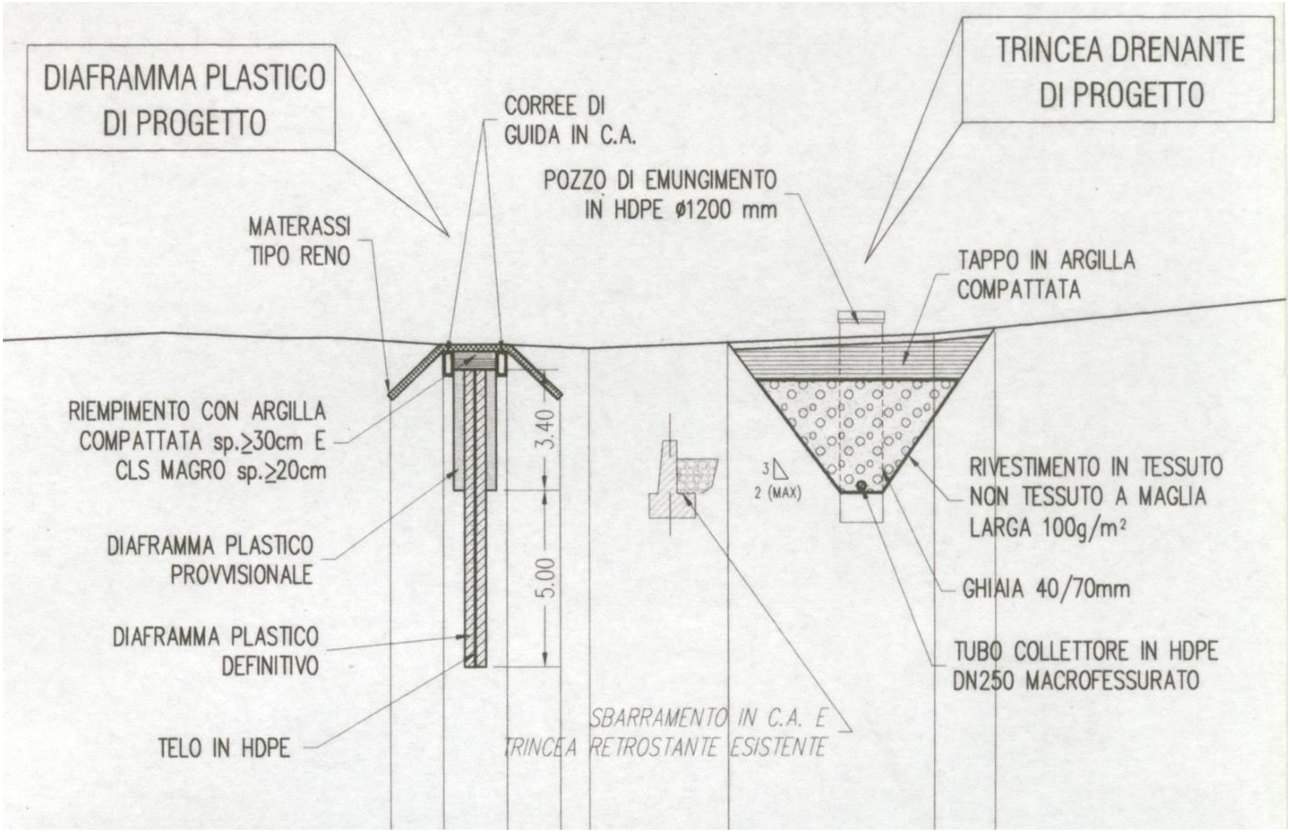


Figure 33. Syndial project for plastic diaphragm and drainage trench

The reclamation project therefore envisaged the emergency handling of thousands of cubic meters of materials (waste and waste mixed with the ground) and their relocation in Zone A1, an area where there were already about 1.3 millions of cubic meters of waste and at the same time the implementation of interventions aimed at completely isolating Zone A1 from the external environment through containment works. In particular, the choice of containment in Zone A1 derived from the technical impossibility of clearing 1,300,000 m3 of industrial waste, stacked in Area 1. Furthermore, containment was particularly suitable for the Cengio site, as it exploited the presence of a strong marl substrate (over 150 m) present at modest depths which guaranteed the isolation of the bottom. [38] It is worth highlighting that the containment measures implemented to isolate contaminated areas, such as historic landfills, often lack an impermeable layer at the base. Taking into account the presence of a strong and shallow marly layer at the Cengio site, the proposed containment intervention aimed to ensure the necessary insulation properties for creating landfills for hazardous waste. The proposed intervention also included provisions for long-term monitoring of the project to ensure its effectiveness and compliance with the required standards. The objective was to create a secure and controlled environment to manage hazardous waste at the site.

As regards the disposal of saline waste contained in the basins located in Zone A1, the lagoons were emptied by extracting the sodium salts using cranes located on the edges of the basins, the salts were subsequently melted, the solution was titrated and conferred in tanks. In special plants the salts were dried and packaged in big-bags, which were transported by train to Germany, to be stored permanently in rock salt mines, for example in the TEUTSCHENTHAL Mine, located between the cities of Halle and Teutschenthal near Leipzig.

Figure 34. Extraction of salts

Figure 35. Train with big-bags

The cost for storing saline waste from ACNA was 0.15 euro/kg including rail transport (storage only 0.07 euro/kg). The cost of the solution does not include the treatment of waste solution and drying. The "Big-bags", made in Turkey, costed 18 euros each. [37]

The remediation of Zones A2, A3, and A4 was carried out through excavation and removal methods. This approach was chosen after a thorough assessment of applicable technologies, which concluded that selective excavation was the most established and effective method. It allowed for the separation, recovery, and re-utilization of a significant amount of land required for the final restoration of the area. [38]

The heterogeneous nature of the contamination present on the site made it clear that relying on a single technology would not effectively achieve the desired remediation goals. Partial treatments aimed at reducing toxicity were found to be costly, operationally challenging, and posed safety concerns, while offering only marginal reductions in environmental impact. In comparison, excavation-based reclamation was the most suitable approach, especially considering the need to clear the areas for reindustrialization as soon as possible.

The decision to relocate materials resulting from excavation and removal activities from other areas of the site to Zone A1 was driven by the necessity to effectively isolate Area A1 through containment measures comparable to those employed for hazardous waste landfills. Given the requirement to quickly stop the migration pathways of contamination and protect both human health and the environment, the most environmentally, socially, and economically sustainable solution was to utilize Zone A1 for managing the materials derived from other areas.

This approach enabled the on-site management of over one million cubic meters of materials, which would have otherwise needed to be transported to external disposal sites. Transporting such a massive volume of materials would have consumed significant residual capacity and resulted in substantial impacts, primarily associated with the handling and transportation processes.

By consolidating the materials in Zone A1, the project could efficiently utilize available space, minimize transportation-related impacts, and establish effective containment measures to safeguard against contamination migration. This approach aligned with the principles of environmental sustainability, social responsibility, and economic efficiency.

Additionally, implementing an off-site disposal intervention would have incurred costs amounting to hundreds of millions of euros, so financially unsustainable. Such an approach would have contradicted the fundamental principles outlined in the main European guidelines concerning the sustainability of remediation and contaminated sites. Moreover, the environmental benefits achieved through off-site disposal would have been practically negligible in comparison to the significant costs involved. Considering these factors, pursuing off-site disposal was not a viable or environmentally compatible option

As regards the embankment protection works against hydraulic risk and drainage, in order to avoid water contamination due to possible floods, ENIRewind has built an engineering structure with high technological value which consists in the construction of an embankment approximately 2,500 meters long founded on a layer of impermeable soil, marl, in which a plastic barrier diaphragm has been positioned for the wastewater. The structure, among the first in the world built with this cutting-edge technology, can withstand an overflow of 1,750 m3 of water per second, guaranteeing site safety. [40]

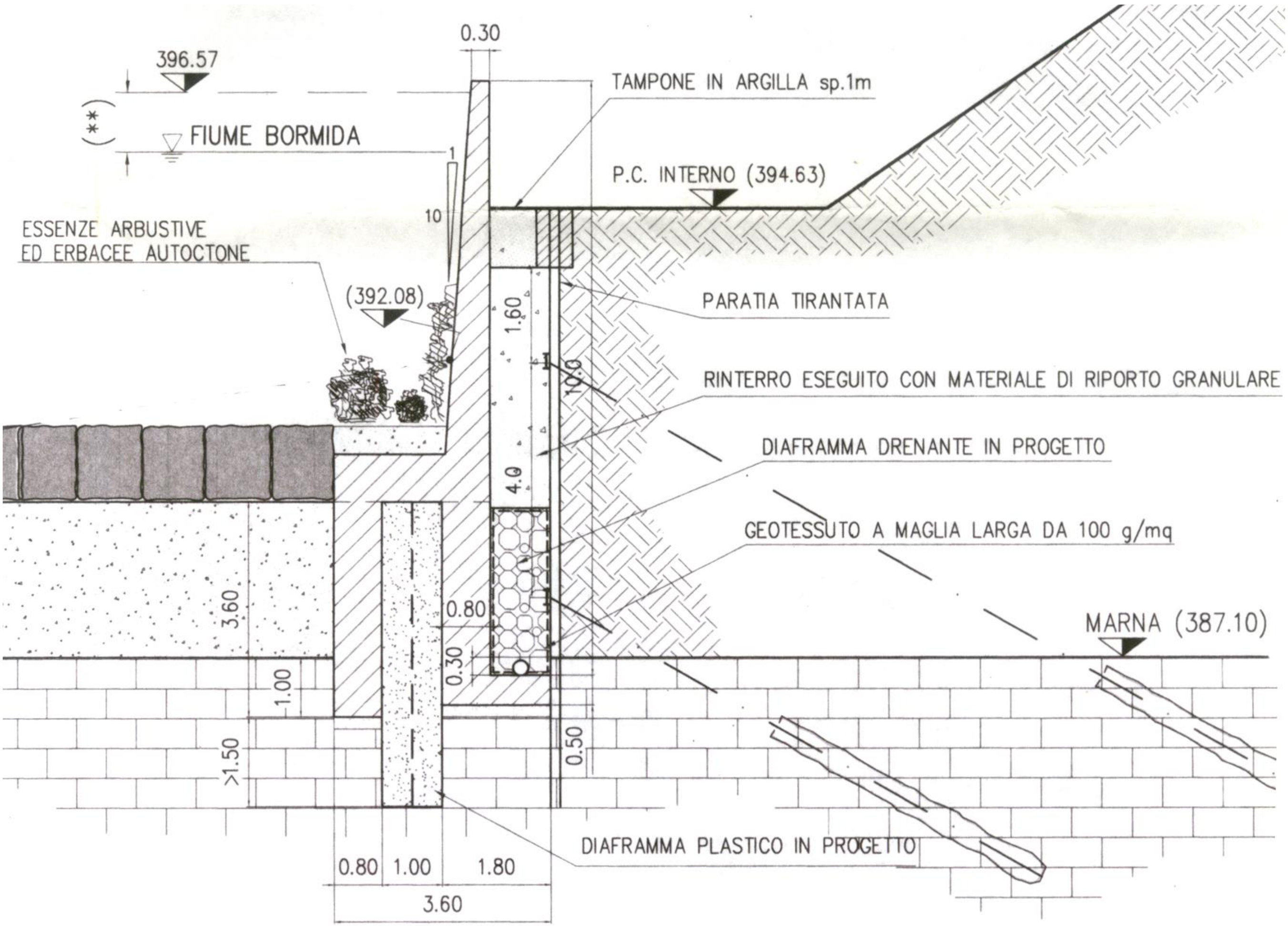


Figure 36. Embankment Project

Figure 37. Construction works

Regarding surface water and groundwater, enhanced bioremediation techniques and pumping and treat systems were used. Hundreds of thousands of cubic meters of water were thus treated per year (for example 757,000 cubic meters in 2021, and 783,000 cubic meters in 2022). [40]

The definitive projects, approved in 2006, were: the definitive project for permanent safety, disposal, and environmental restoration for zone A1; the final reclamation project for zones A3 and A4; the final reclamation project with hydraulic confinement and safety measures for zone A2.

Over the years, ENIRewind has achieved some objectives of fundamental importance, in particular [33]:

• The disposal of saline waste was completed: the Lagoons emptying operations lasted 4 years and the salts were disposed of in 4 different underground deposits (former mines) in Germany, with 185 journeys by train.

• The plastic diaphragm separating area A1 from area A2 was created.

• Construction of a rainwater drainage system.

• The land reclamation works in area A2 have been completed.

• The works envisaged upstream of the site were carried out aimed at intercepting the surface water entering the site.

• The site's internal water containment system was created.

• Demolition of former industrial buildings

• The soil/sediment/waste removal works from the A3 floodplain area and the A4 area, the former Pian Rocchetta landfill, have been completed.

The Province of Savona, which controlled the reclamation activities, has already issued the certifications of "completamento bonifica e restituzione delle aree ad usi legittimi" of areas A4 (Pian Rocchetta landfill) and A2. [33][40]

Detailed investigations are currently in progress for the A3 area, specifically the floodplain, which has not yet been certified. Additional characterizations are also being conducted for certain areas adjacent to the site. These investigations were initiated after contaminants associated with ACNA's production were discovered in groundwater, with concentrations surpassing the regulatory limits. Efforts are being made to assess and address the extent of contamination in these areas.

Regarding zone A1, safety measures are still being implemented and are ongoing. These measures are crucial to ensure the safety and integrity of the site. The implementation of safety protocols and precautions is necessary to mitigate potential risks associated with the site and its remediation process.

The costs incurred by ENIRewind for the environmental remediation interventions and activities amounted to approximately 293 million euros in 2016, approximately 372 million euros in 2021 and approximately 380 million euros in 2022 and estimation of further costs of approximately 40 million euros; with a CAPEX (costs to be incurred) and an OPEX (annual management costs) of respectively around 17 and 1.4 million euros in 2021 and around 28 and 2 million euros in 2022. [40]

In conclusion, the public studies carried out by ARPAL and ARPAP have highlighted, through hydrogeological and hydrochemical monitoring, that the Bormida river has passed from a bad/scarce qualitative state to a good qualitative state, confirming the goodness of the works carried out.[32][33][38][40][41][42]

The studies also revealed a recovery in the well-being of the ecosystem, with sightings of birds, mammals and species of fish, invertebrates and crustaceans that had completely disappeared from the area over the decades, as well as a strengthening of the autochthonous vegetation, thanks also to ecological restoration activities done by ENIRewind. [32][41][42]

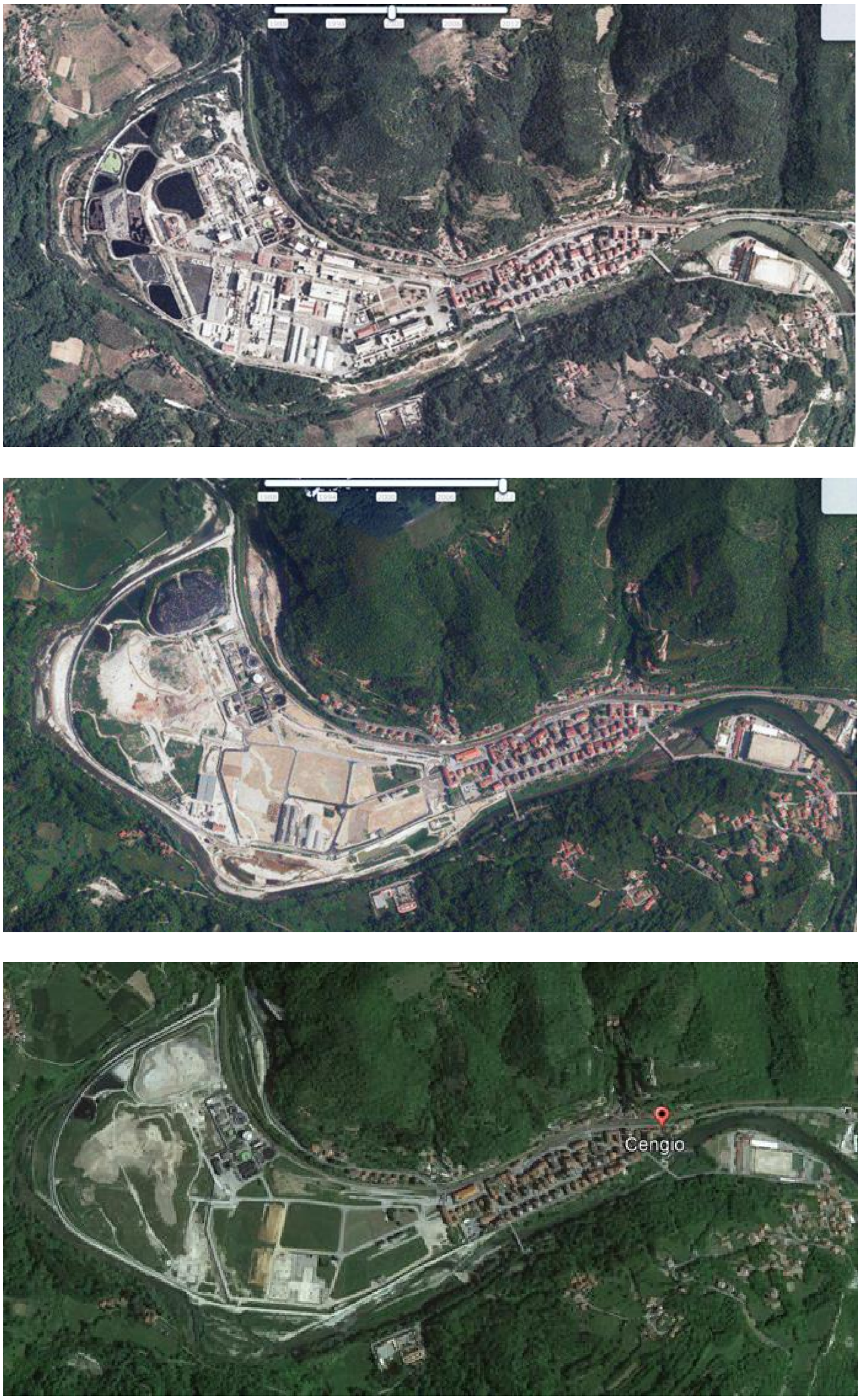


Figure 38. Comparison between the state of the former ACNA site of Cengio in 2000 (above), in 2012 (central) and 2016 (below)

Based on the currently available data, there is reasonable confidence in the effectiveness of the interventions that have been completed or are nearing completion. It is important to acknowledge that these interventions, by their nature, may not have completely eradicated the contamination. However, the data available today confirm that contamination is confined and not posing a threat to the environment in the vicinity of the site. [38][41][42]

Through the remediation measures, the impact of the contamination has been significantly contained and controlled. While residual contamination may still be present, it is being managed to prevent any adverse effects on the surrounding environment. This provides reassurance that the interventions have been successful in mitigating the potential risks associated with the site's contamination.

Anyway, to fully address the environmental situation of the site, it is crucial to ensure the successful completion of the planned remediation works, ongoing monitoring of the containment of contamination, adherence to environmental standards and proper maintenance of implemented safety measures, in order to ensure the long-term effectiveness of the interventions.

The remediation efforts undertaken by ENIRewind at the Cengio site have been significant, considering the severe contamination resulting from over a century of industrial activity, a large portion of which occurred without adherence to environmental standards. Moreover, during these years, the site of Cengio faced a deep-rooted social and economic crisis.

However, despite these challenges, the environmental remediation project has achieved remarkable objectives while adhering to a sustainable approach and environmental compatibility. The remediation efforts have aimed to restore the site's environmental condition and promote the well-being of the surrounding community. By addressing the historical contamination and implementing sustainable practices, ENIRewind has made notable progress in bringing positive changes at the site. Continued dedication to the planned works, monitoring, and maintenance, as stated previously, will be essential to sustain the achieved outcomes and ensure the long-term environmental recovery of the Cengio site.

6. Conclusions

Overall, all the topics declared in the introduction were described, establishing at the end a well-defined link between the role of ecosystems and mitigation and adaptation to the causes and consequences of Climate Change. The global picture that comes out is that it is fundamental and crucial to safeguarding and protect the existing ecosystems from non-environmentally compatible human activities, to maintain them healthy, and mostly important, to restore and remediate, as soon as possible, all the environmental damage occurred that could have deteriorated or destroyed these ecosystems.

Moreover, this thesis has demonstrated, through the presentation of the case study, how industrial activities carried out without adequate control and environmental compatibility criteria can deteriorate the health of an ecosystem. In fact the Cengio and Saliceto SIN, after the influence of ACNA century long industrial activities, was characterized by a complete deteriorated state of the ecosystems, and natural health level of the environment as regards both the soil, the groundwater and the Bormida River, with millions of cubic meters of waste, polluted and dangerous waste, and also substantial level of contaminants present on the site, in highly variable concentrations, like arsenic, iron, mercury, copper, manganese, lead, zinc, aromatic amines, nitrobenzenes, tetrachlorethylene, tetrachlorobenzene, benzene, chlorobenzene, PAHs, naphthalene, PCBs, phenols, naphthalene sulphonic compounds, halogenated aromatic compounds.

To restore the site, the remediation technologies and restoration activities of ENIRewind, which have been ongoing for approximately 20 years, were technologically advanced and difficult from an engineering point of view, and in some case only capable of partially remediate to the environmental disaster. Moreover, the economic engagement was very high, in terms of hundreds of million euros, and these numbers do not take into account all the costs related to the health issues caused to the population during the years, the environmental benefits of biodiversity and aesthetic value vanished, and the loss of economic activities, agricultural activities and revenues related.

However, ENIRewind, even if has not completely eliminate the contamination of the site, has achieved remarkable objectives in managing the waste, the contaminations, the pollution levels, the state of the Bormida River and its ecosystem and the groundwater, and also the related issues, such as infiltration, percolation, flood risks, and others. From the public studies carried out by ARPAL and ARPAP has been highlighted, through hydrogeological and hydrochemical monitoring, that the Bormida River has passed from a bad/scarce qualitative state to a good qualitative state, confirming the goodness of the works carried out. The studies also revealed a recovery in the well-being of the ecosystem, with sightings of birds, mammals and species of fish, invertebrates and crustaceans that had completely disappeared from the area over the decades, as well as a strengthening of the autochthonous vegetation, thanks also to ecological restoration activities done by ENIRewind.

In conclusion, this thesis has also outlined, through the presentation of the case study, how challenging it is, from a regulatory, legislative, social, technological, time-consuming, and economic perspective, to restore the state of a destroyed ecosystem.

This conclusion, when connected to the initial and central part of the thesis, will underline the propositions of the IPCC reports on the importance of safeguarding ecosystems in facing climate change. In fact, it will make understand how, considering the cumulative effect of anthropogenic pressures and environmentally incompatible activities scattered worldwide, some of which are significantly larger in scale compared to the case study (which represents only a localized event in a microregion of a relatively small European Nation), this can lead to the complete disintegration of ecosystems' functions as regulators of normal climate equilibrium.

Additionally, it will result in the loss of natural resilience to the already confirmed, certified, imminent, and present impacts of climate change. Ultimately, it will require substantial global economic expenditure for the remediation of damaged ecosystems (where possible) and will exact an economic and human cost in terms of lives, health, and well-being due to the absence or degraded state of these ecosystems.

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