Chapter 4
Atlas of World Agriculture and Food Systems in the Face of Climate Change

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Abstract The atlas presented in this work analyses the challenges of climate change for agri-food systems, first through the lens of (1) greenhouse gas emissions, then (2) the impacts of climate change on the land sector, followed by (3) the question of the effects of climate change and mitigation challenges, and finally (4) by adopting an analysis by major regions.

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4.1 Introduction and Methods

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The atlas presented in this work analyses the challenges of climate change for agri-food systems, first through the lens of (1) greenhouse gas emissions, then (2) the impacts of climate change on the land sector, followed by (3) the question of the effects of climate change and mitigation challenges, and finally (4) by adopting an analysis by major regions.

4.1.1 Greenhouse Gas Emissions from Agri-Food Systems

We first wanted to emphasise that although agri-food systems are responsible for nearly a third of greenhouse gas (GHG) emissions (Crippa et al. 2021; Rosenzweig et al. 2020; Tubiello et al. 2022), this global figure conceals strong and sometimes counter-intuitive disparities, as illustrated in Fig. 4.1. This figure indeed reminds us that the main continent emitting agricultural greenhouse gases is Asia, with nearly 39% of all agricultural greenhouse gases. Rice cultivation there generates significant amounts of methane, as does the intensive use of nitrogen fertilisers with nitrous oxide. The export of agricultural products results in additional emissions due to transport. The Americas are the second largest continent emitting greenhouse gases (30%).

Within this region, intensive agricultural systems in the United States and Canada—particularly maize and soybean production for animal feed—are associated with a large carbon footprint. This is further increased by the long-distance

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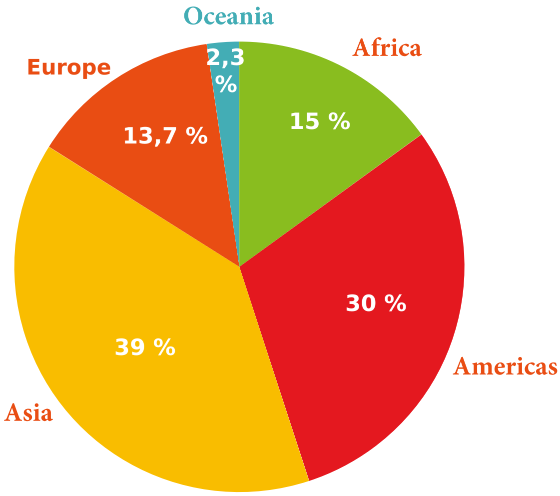
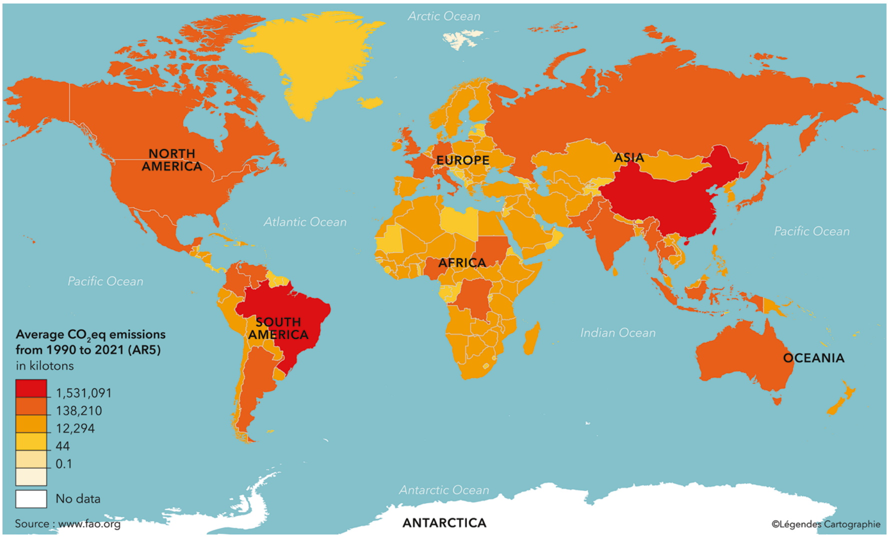


Fig. 4.1 Share of average eq CO_2 emissions (AR5) from agricultural and food systems by continent between 1990 and 2021. (Source: FAO (2024))

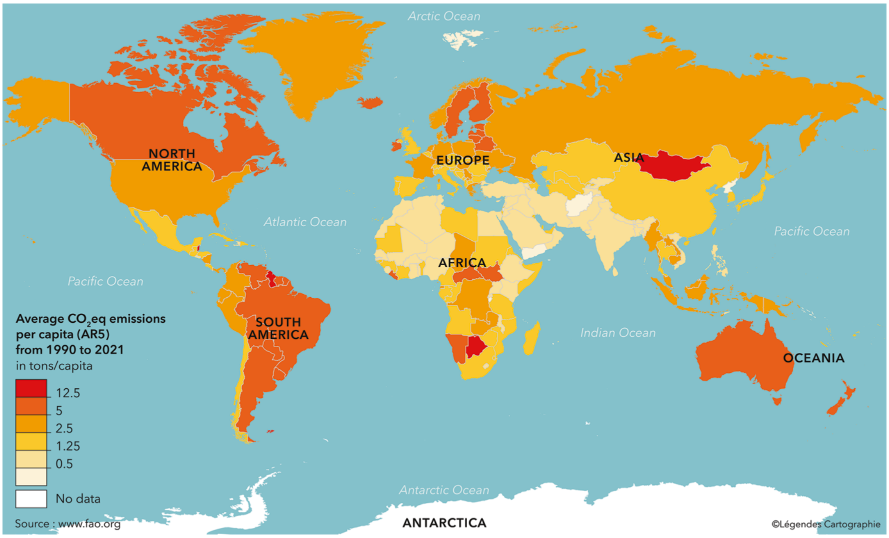
transport of these products and by high levels of consumption of processed foods. In Latin America, between 50% and 60% of total emissions come from the agricultural sector, especially in Brazil and Argentina, both major exporters of beef and soybeans.

In Africa, the carbon footprint of agricultural and food systems, in relation to the population and food production, is surprisingly high (15% of global sector emissions), and is mainly explained by land use change (deforestation in Central Africa) and low agricultural productivity. These global figures, however, mask a great geographical diversity. Central Africa is responsible for 35% of the greenhouse gas emissions linked to the continent's food systems, ahead of West Africa, responsible for 28% of these. North Africa accounts for only 12% of the total. Despite more efficient agricultural practices in Europe (13.7% of agricultural emissions) and effective EU climate policies, livestock remains a major source of greenhouse gas emissions also linked to food processing and its transport chains. Finally, in Oceania, the use of land for extensive grazing is a source of emissions, although the relatively small population limits its overall impact.

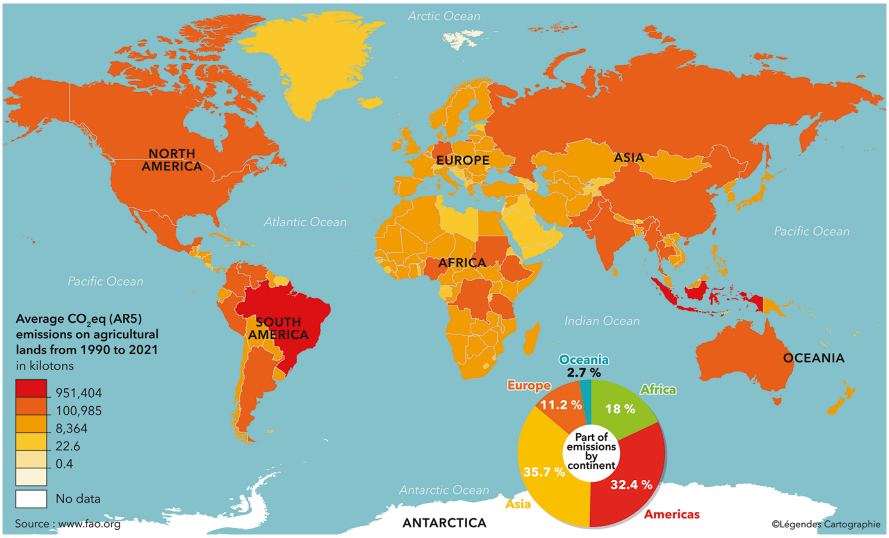
Having outlined these global figures, we then sought to deepen the analysis in the following section in order to better understand the various challenges linked to emissions from agri-food systems. The first ten maps proposed (Maps 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10) are from the FAOSTAT database (FAO 2024) and represent the average emissions for the period 1990–2021 by country. They aim



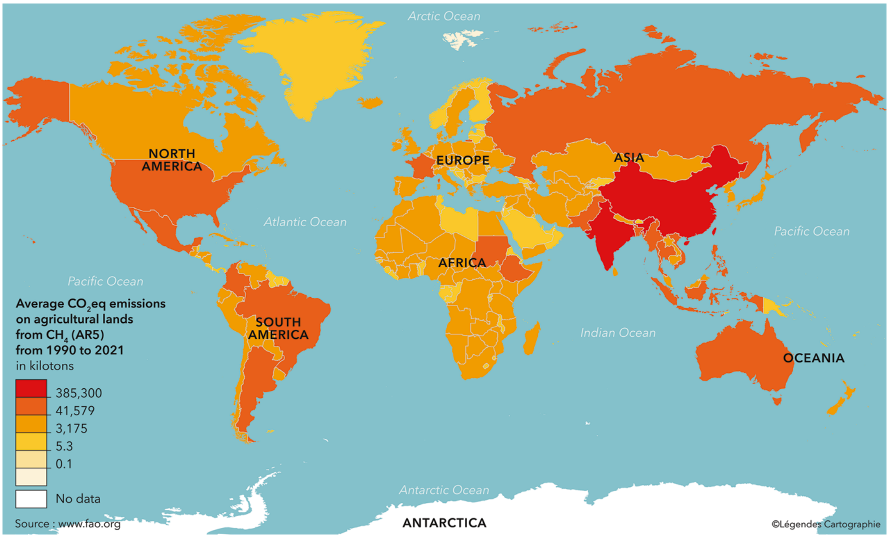
Map 4.1 Average CO_2 eq emissions from 1990 to 2021 (AR5)



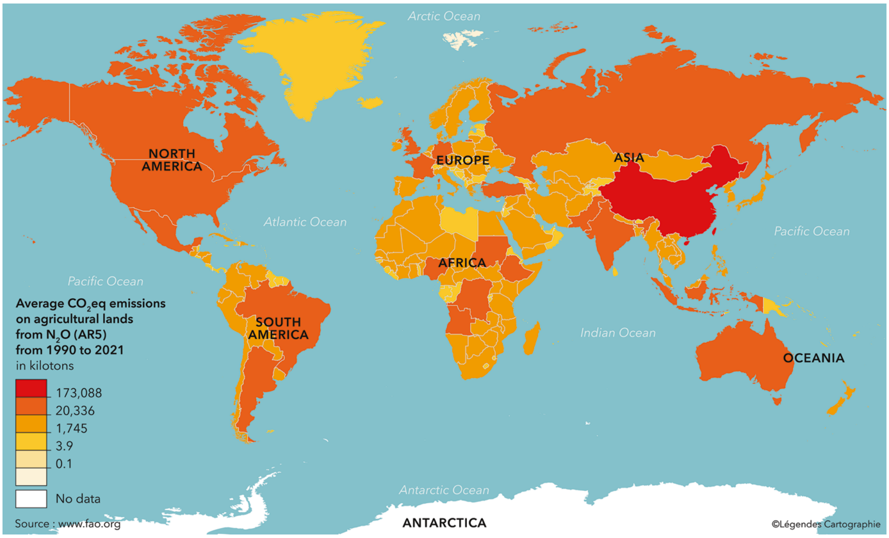
Map 4.2 Average CO_2 eq emissions per capital from 1990 to 2021 in tons/capita



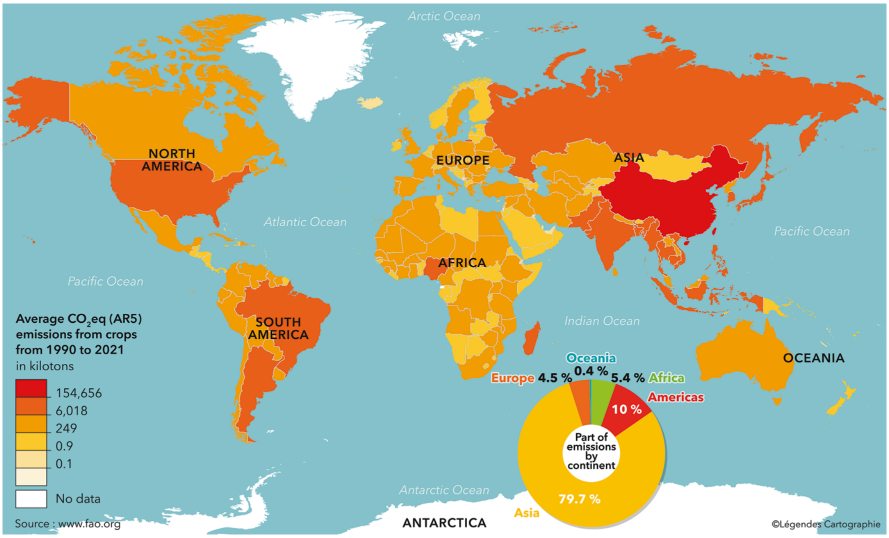
Map 4.3 Average CO_2 eq emissions on agricultural lands from 1990 to 2021 in kilotons(AR5)



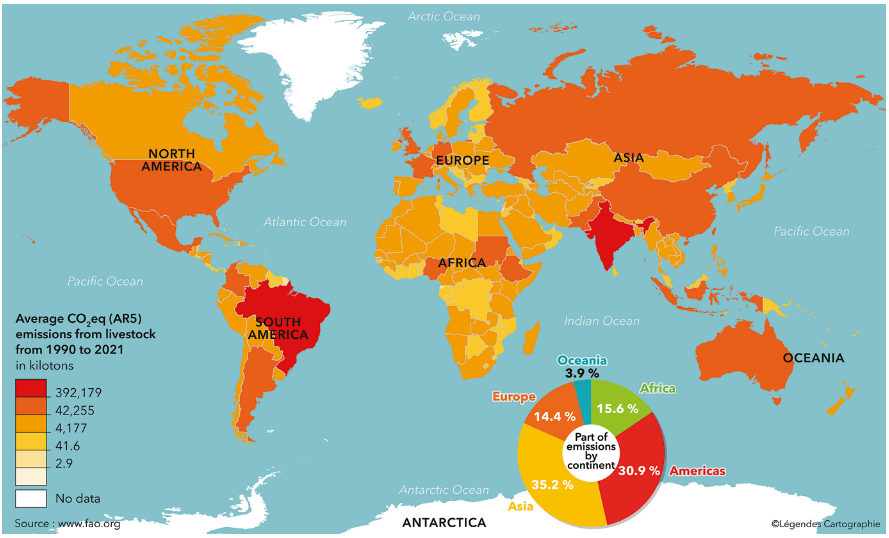
Map 4.4 average CO_2 eq emissions on agricultural lands from CH_4 (methane) from 1990 to 2021 in kilotons (AR5)



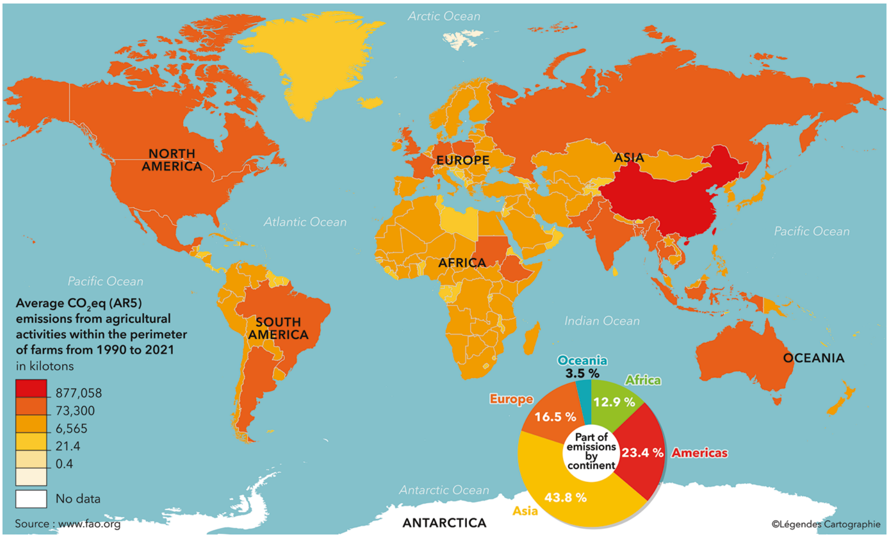
Map 4.5 Average CO_2 eq emissions on agricultural lands from N_2O (Nitrous oxide) from 1990 to 2021 in kilotons (AR5)
Carbon sequestration potential from natural forest regrowth



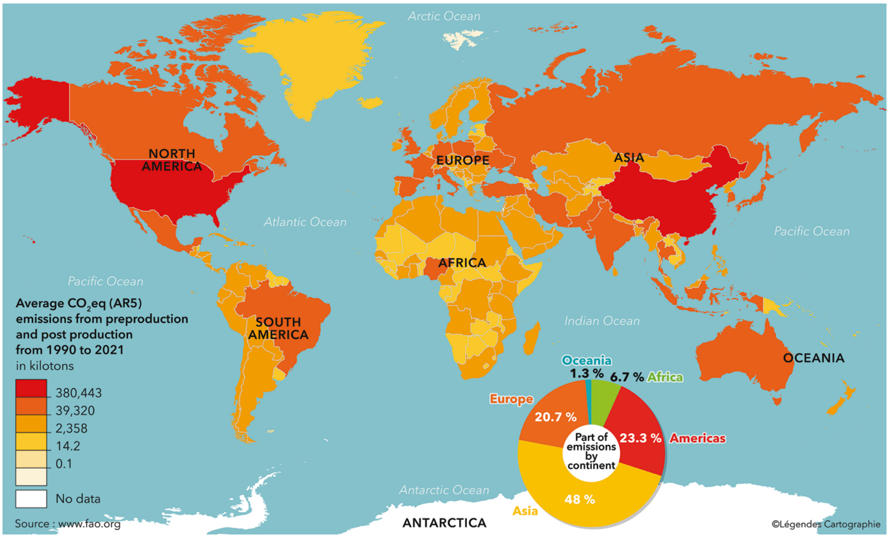
Map 4.6 Average CO_2 eq emissions from crops 1990 to 2021 (AR5) in kilotons



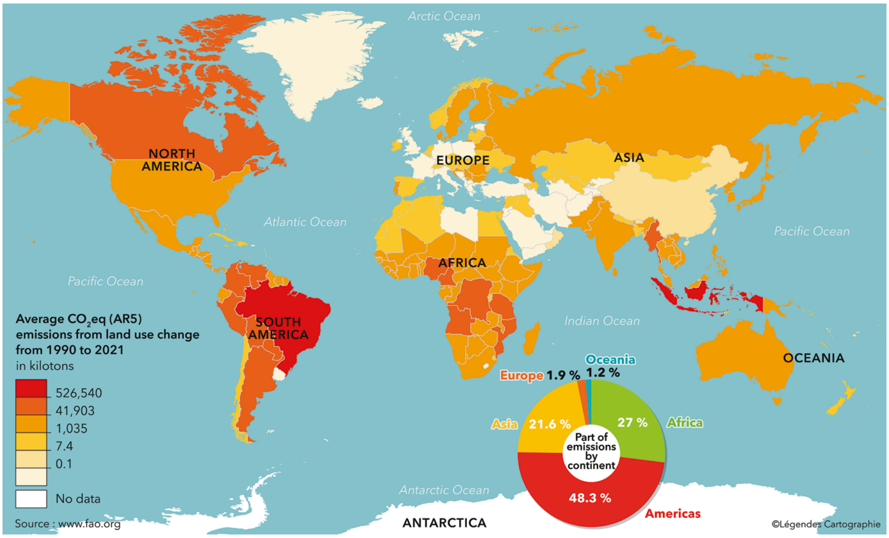
Map 4.7 Average CO_2 eq emissions from livestock 1990 to 2021 (AR5) in kilotons



Map 4.8 Average CO_2 eq emissions from agricultural activities within the perimeter of farms from 1990 to 2021 in kilotons



Map 4.9 Average CO_2 eq emissions from preproduction and post production from 1990 to 2021 in kilotons



Map 4.10 Average CO_2 eq emissions from land use change from 1990 to 2021 in kilotons

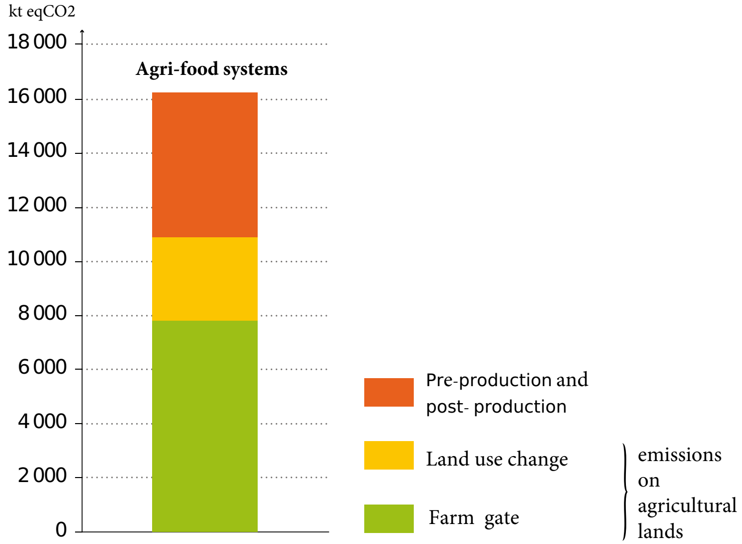


Fig. 4.2 Average CO_2 emissions by sector (in kt eq CO_2), between 1990 and 2021. (Source: FAO (2024))

to clarify the issues related to emissions from the agri-food sector (from pre-production stages, to production and post-production stages) using different variables (emissions by country, per capita, at each stage of the agri-food system, etc.).

Emissions indeed come from multiple sources (Box 4.1) and vary according to biophysical factors, biogeographical factors, production systems, agricultural practices, types of food produced and consumed, and waste management systems. As the FAO chart below (Fig. 4.2) reminds us, half of the emissions are attributable to production activities within the farm (*farm gate*). Added to the GHG emissions related to land use change, emissions on agricultural lands produce nearly two-thirds of the emissions from agri-food systems. However, pre-production and post-production activities constitute an increasing share of these system emissions.

The categories used to distinguish between emissions from land-use change, on-farm emissions, and emissions related to the pre-production and post-production stages are based on the classifications employed by the FAO (see Table 1 in Introduction).

4.1.2 The Impacts of Climate Change on the Land Sector

The following section, focusing on the impacts of climate change on the land sector, proposes through Map 4.11 (based on the IPCC's 2023 report) a more in depth understanding of the impacts of climate change on agricultural productivity and climate vulnerabilities.

4.1.3 Carbon Storage

The following section addresses the issue of carbon—its storage, fluxes, and sequestration by the land sector—through six distinct maps (Maps 4.12, 4.13, 4.14, 4.15, 4.16 and 4.17). These maps are based on data from the Global Soil Partnership, the Impact4Soil platform, and Global Forest Watch platforms.

Box 4.1 Types of GHGs and global warming potentials

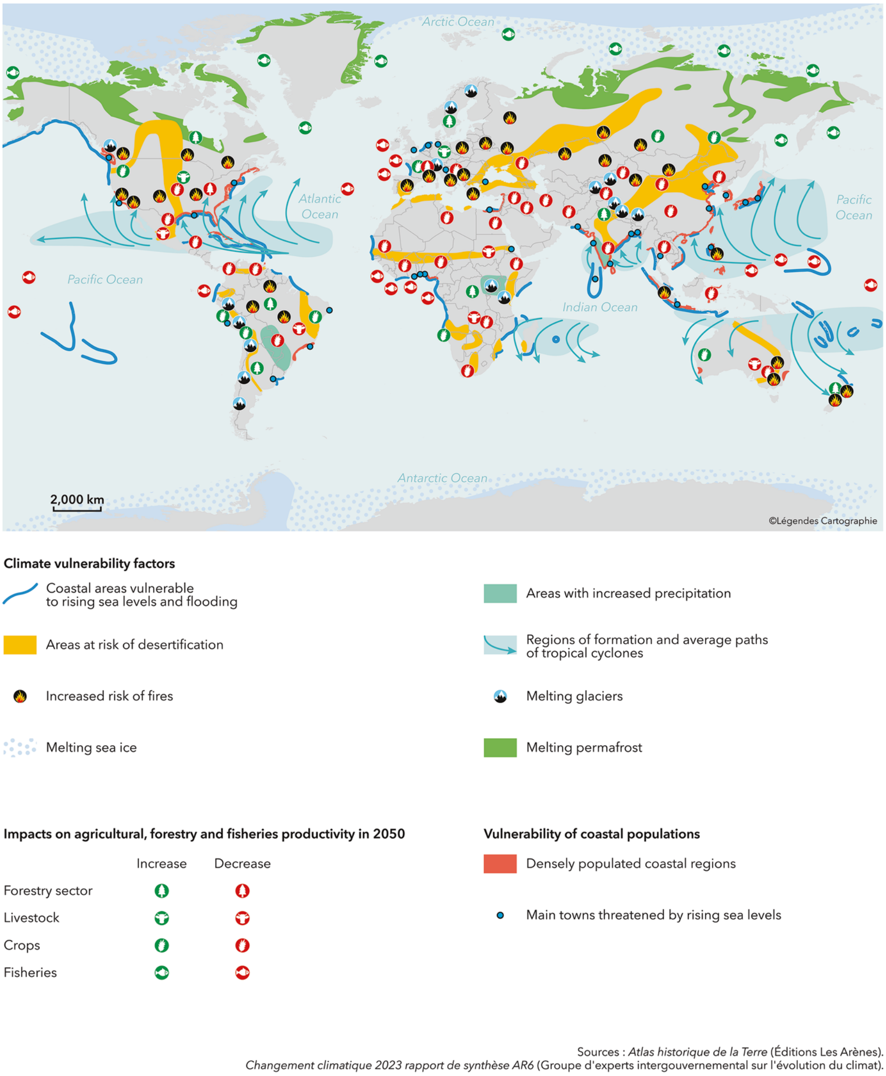
The tonne of carbon dioxide equivalent (CO_2e) is a unit introduced in the IPCC First Assessment Report (IPCC 1990), allowing emissions from different greenhouse gases (GHGs) to be aggregated after conversion.

This unit is based on the Global Warming Potential (GWP), an index that compares the warming effect of a greenhouse gas relative to carbon dioxide (CO_2) over a chosen time period. In other words, the GWP of a gas is the ratio of the warming caused by the release of a given mass of that gas at the beginning of the period, compared to the warming caused by the same mass of carbon dioxide. By definition, the GWP of CO_2 is always equal to 1. The warming effects are calculated over a set time frame, beyond which any residual effects are deliberately excluded. The most commonly used time horizon is 100 years, referred to as GWP100.

Other gases, such as methane (CH_4) and nitrous oxide (N_2O), have much higher GWPs than CO_2 because they are more efficient at trapping heat in the atmosphere, even though they are present in smaller quantities:

- Methane (CH_4): GWP ≈ 28 times higher than that of CO_2 over 100 years (according to the IPCC Sixth Assessment Report). This means that the release of one tonne of CH_4 is equivalent to the release of 28 tonnes of CO_2. Among the major GHGs, CH_4 has a relatively short atmospheric lifetime. The IPCC (2021) estimates this at 11.8 years;
- Nitrous oxide (N_2O): GWP ≈ 273 times higher than that of CO_2 over 100 years (according to the IPCC Sixth Assessment Report). In other words, emitting one tonne of N_2O is equivalent to releasing 273 tonnes of CO_2. N_2O has a long atmospheric lifetime, estimated by the IPCC at 109 years.

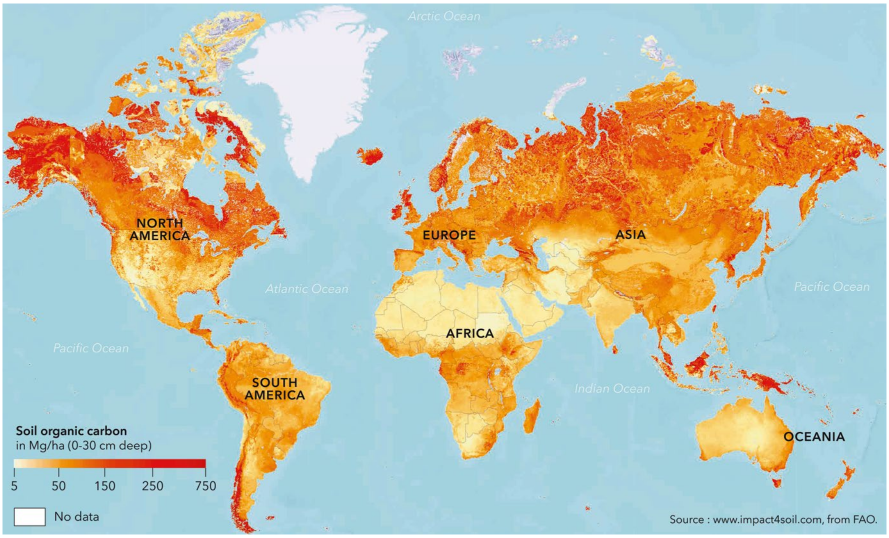
Furthermore, GHG emissions can be expressed in kilotonnes (kt), in megatonnes (Mt or million tonnes), in gigatonnes (Gt or billion tonnes), or even in petagrams (Pg) equivalent to Gt.



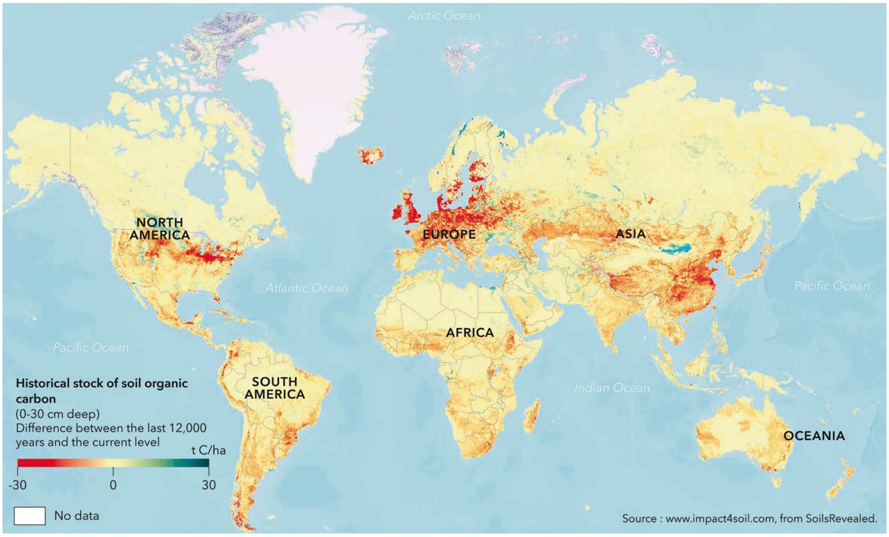
Map 4.11 Climte vulnerability factors, Impacts on agricultural, forestry and fisheries productivity in 2050 and vulnerability of coastal populations

4.1.4 Evolution and Impacts of Climate Change on the Land Sector by Continent

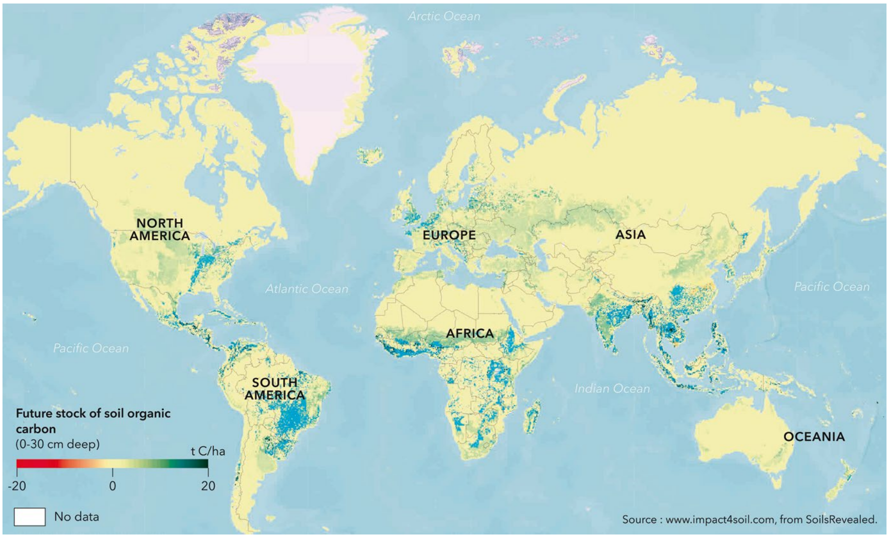
Finally, in the last section of this chapter, six analyses at the scale of continents are proposed. For Africa, Southeast Asia, Central and South America, small island states and territories of Oceania, Europe and North America, the atlas analyses the



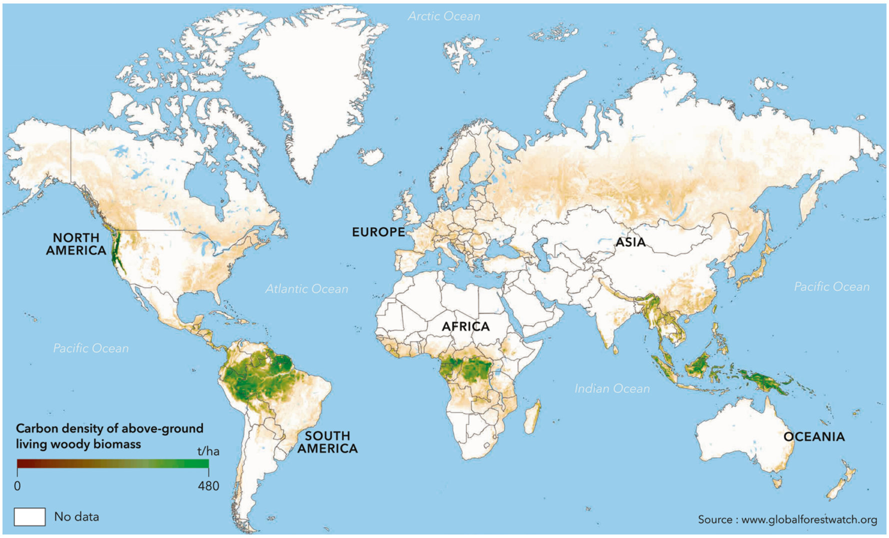
Map 4.12 Soil organic carbon stock in Mg/ha (0-30cm depth)



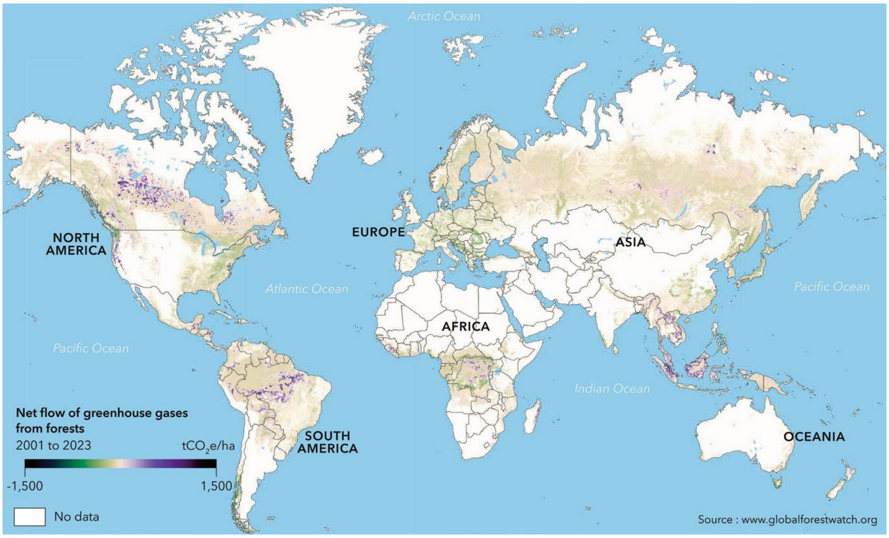
Map 4.13 Historic soil organic carbon stocks in tC/ha (0-30 cm depth)



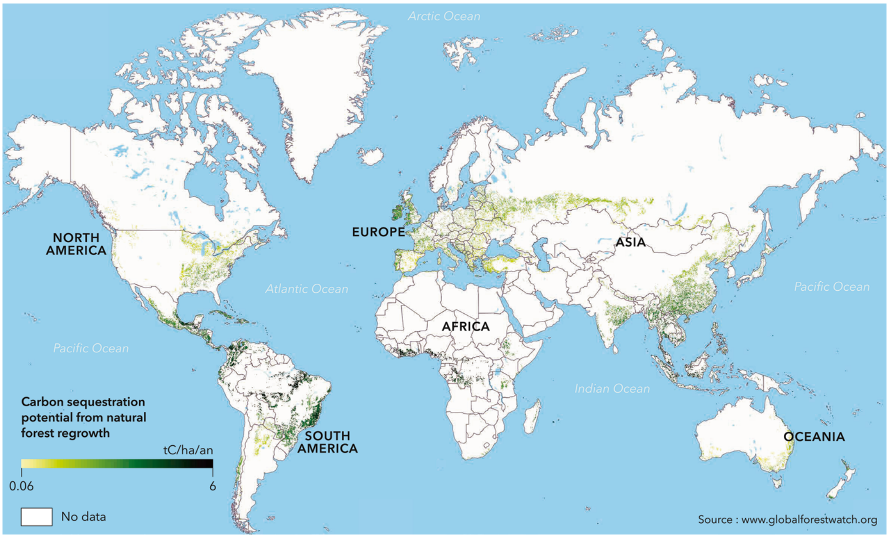
Map 4.14 Future stock of soil organic carbon in tC/ha (0-30 cm depth)



Map 4.15 Carbon density of above-ground living woody biomass



Map 4.16 Net flux of greenhouse gases from forests between 2001 and 2023



Map 4.17 Carbon sequestration potential from natural forest regrowth

past, current and future changes in climatic parameters (temperature, precipitation, occurrence of fires, sea levels). It also briefly discusses the consequences on agriculture, forests, livestock or even on fishery resources. It is therefore clear that, while all continents are affected by the overall rise in temperatures, some regions within them will be more severely impacted than others, along with the agricultural production systems found there.

4.2 Atlas of Greenhouse Gas Emissions from Agri-Food Systems

Marie Hrabanski, Vincent Blanfort, and Julien Demenois

4.2.1 Map of Agri-Food System Emissions by Country Between 2019 and 2021

Emissions from the agri-food sector refer to three different posts: emissions emitted at the plot scale (*farm gate*), emissions related to land use change and emissions related to pre-production and post-production activities. This representation of GHG emissions from the agri-food sector combines the total of all GHGs by country expressed by averaging the period 1990–2021 (Map 4.1). There are significant disparities between industrialised countries and others. The Chinese and Brazilian agri-food systems are the largest GHG emitters. Emissions produced by China are particularly high due to its intensive agricultural production (the world's largest rice producer) and its livestock industry (40% of agricultural emissions). In Brazil, it is also the intensive agri-food production (about 70% of Brazil's total emissions) and the conversion of vast areas of forests into agricultural land that explain these high emissions.

In second place are Indonesia, the United States, the European Union (EU), India, Russia and Australia. The agri-food systems of these countries (or group of countries) are also particularly emitting, due to the volume of their agricultural productions and associated sectors.

In Africa, the situation varies, but most countries are at medium to low emission levels. However, Africa was Originally, in 2019, 17% (15% for Sub-Saharan Africa and 2% for North Africa) of global GHG emissions were linked to agri-food systems, more than the United States (9%) and the EU (7%). However, there are significant disparities from one region or even one country to another. In Sub-Saharan Africa, these systems emit slightly less GHG per capita (2.3 t CO_2 eq) than in the EU (2.6 t CO_2 eq). But food production per capita is also much lower there (which partly explains the food insecurity of the sub-region). In proportion to the value of food production, the quantities of GHGs emitted south of the Sahara are therefore more than twice as high as in the EU. They are even five times higher if we take into account land use change (deforestation in Nigeria and the Congo basin and cultivation of grazing areas).

This initial global analysis is complemented by a comparison of global emissions by major sector (Fig. 4.3). Livestock activities (Chaps. 10, 16 and 24), and net forest conversion (Chap. 9) are the most impactful, but other sectors can also significantly increase these emissions if we add up the sub-sectors they involve (example of crops with fertiliser manufacturing, energy consumption, etc.).

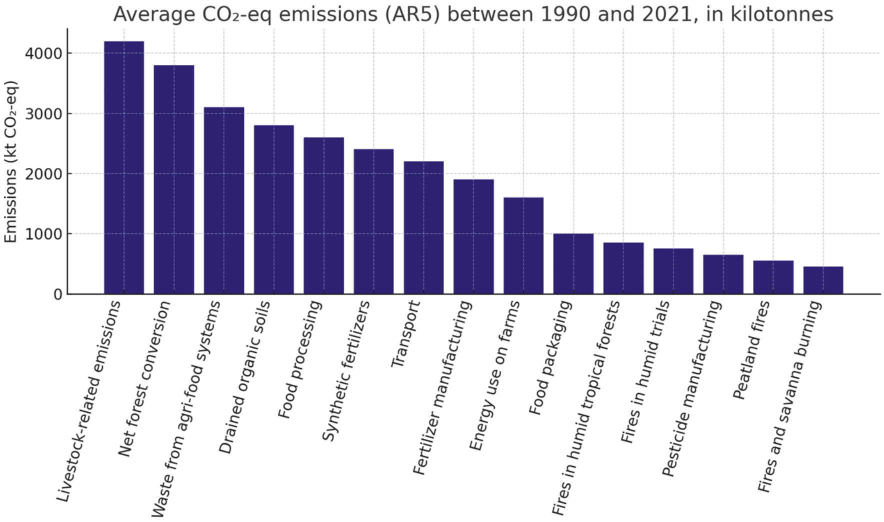


Fig. 4.3 Comparison of global emissions by major sector. (Source: www.fao.org)

4.2.2 Map of Agri-Food Sector Emissions Per Capita

It is essential to put national emission figures into perspective through the lens of each country's population. The map of agri-food sector emissions per capita (Map 4.2) thus presents a completely different vision than the previous one: the countries with the highest emissions in volume are no longer at the top of the ranking. South America, Canada, Northern Europe still have a high ratio due to the impact of agricultural expansion and forestry exploitation at the expense of forests. Western Europe, Asia and Africa have lower per capita scores than their gross emission volume due to their high population density.

Some countries with average low national emissions are propelled to the top of the ranking due to a very low population. Notably, Mongolia, due to a very high ratio of livestock per capita. For the same reasons, Botswana and Namibia are characterised by an agricultural sector (especially livestock) that represents 10–15% of their total GHG emissions.

4.2.3 Map and Graph of Agricultural Land Emissions

In reference to Fig. 4.2 (see the introduction to this chapter), the synthetic definition of agricultural land includes: emissions emitted at the farm gate (from entry to exit, excluding prior and subsequent stages) thus excluding pre-harvest and post-harvest processes; and land use change.

The emissions from this sector therefore reflect the impacts of strict farm production activities combined with land use changes aimed at expanding agricultural areas.

According to the FAO, agricultural lands include areas used for cultivation, for pastures, and for related agricultural activities. These include arable lands (temporary crops, fallow lands), areas allocated to perennial crops (fruit trees, plantations), and permanent meadows used for livestock farming. These lands can vary according to agricultural systems and local conditions, also encompassing natural resources essential for agricultural productivity, such as soils, vegetation, and water resources.

This definition reflects an integrated approach, taking into account not only soils, but also environmental and socio-economic factors related to sustainable land use. Agricultural lands play a key role in global food supply, ecosystem conservation, and rural development.

The Asia region alone contributes to nearly 36% of agricultural land emissions, mainly due to methane emissions, due to rice cultivation and intensive livestock farming (Maps 4.3 and 4.4). There are very high emissions in insular Southeast Asia linked to deforestation for palm oil production.

It is closely followed by the American continent with a strong impact of deforestation for crops and pastures in the Amazon. The United States and Canada have highly mechanised agricultural systems, which results in CO_2 emissions related to the use of fossil fuels. The production of beef, pork, and poultry is intensive, which increases methane emissions associated with the intensive use of synthetic fertilisers for major crops such as corn, soybeans, and wheat.

Africa, with 18% of emissions, is characterised by regional trends. In West and East Africa, livestock activities are a source of methane and extensive agricultural practices such as slash-and-burn agriculture, a major source of N_2O and CO_2. In East Africa, livestock farming is dominant, with high methane emissions due to enteric fermentation. Deforestation in Central Africa is a significant source of emissions. Monocultures and increased use of fertilisers in Southern Africa contribute to nitrous oxide emissions (Map 4.5).

The analysis of greenhouse gas (GHG) emissions from agricultural lands in Europe (11.2%) reflects dynamics specific to this industrialised and technologically advanced region, particularly in Northern Europe. Intensive land use and high mechanisation are controlled by advanced sustainability policies (CAP, Common Agricultural Policy) and practices such as organic farming and conservation agriculture.

Eastern Europe is still in a post-Soviet transition characterised by a gradual increase in agricultural intensity. Intensive practices in horticultural and wine crops can be associated with high input emissions in Southern Europe.

4.2.4 Map and Graph of Emissions Attributable to Crops Worldwide, Between 1990 and 2021

Map 4.6 analyses the GHG emissions produced between 1990 and 2021 by agricultural crops, and in particular by the following productions: wheat, barley, oats, soybeans, potatoes, rice, corn, sugar cane, millet, sorghum, dry beans, rye.

Nearly 80% of GHG emissions from crops are attributable to Asia. Taking into account all types of GHGs, methane emissions from rice cultivation partly explain this particularly high figure. The Americas are the second emitting continent, with 10% of emissions (soybeans, corn, wheat). Europe and Africa are each responsible for about 5% of GHG emissions from crops; these emissions per capita on each of these two continents indicate that GHG emissions from crops in Africa are particularly low. Finally, only 0.4% of GHG emissions from crops are attributable to Oceania.

4.2.5 Map and Graph of Emissions Attributable to Livestock Farming

According to an FAO (2023) assessment, livestock farming accounts for 40% of total emissions from agri-food systems, or about 12% of total anthropogenic GHG emissions globally (see Chaps. 10 and 16). It is methane (CH_4), mainly from the enteric fermentation of ruminants (cows, goats, sheep) and the management of animal waste, which is the main cause with more than half of the emissions linked to animal production. It is followed by carbon dioxide (CO_2, 31%), attributable to land use changes (deforestation for pastures or fodder crops) as well as energy consumption for production and transport. Finally, 15% of these emissions are attributable to nitrous oxide (N_2O) produced by the use of fertilisers and soil management.

Beyond these global figures, GHG emissions from the livestock sector vary greatly depending on the regions of the world. (Map 4.7).

An analysis by major world region shows that Asia and the Americas contribute to two-thirds of global emissions. Asia emits a third of the emissions due to the rapid growth in demand for animal products linked to population growth and urbanisation. China is thus the world's leading producer of pork, and India is the world's leading producer of milk. The American continent also contributes to more than 30% of global emissions, particularly due to the significant numbers of ruminants (Brazil in particular, with the conversion of primary forests into pasture and crops for animal feed).

In Africa, animal production plays a crucial role in food security, livelihoods, and the economy, particularly in pastoral areas: the continent consequently contributes to 15.6% of global GHG emissions. These emissions represent about 10% of the continent's total GHG emissions. Europe is almost on par, despite a more regulated livestock sector in terms of regulations and agricultural practices. The sector represents a dominant share of agricultural emissions in Europe estimated at over 70%, or 10% of the total GHG emissions of the European Union.

The main sources of emissions related to livestock are:

- Enteric fermentation: ruminants (cows, sheep, goats) produce methane (CH_4) during their digestion;
- Manure management: animal waste emits methane (CH_4) and nitrous oxide (N_2O) when it decomposes;
- Animal feed production: the cultivation of cereals and forage used to feed animals generates GHG emissions (CO_2 linked to mechanisation and the use of synthetic fertilisers, N_2O released by soils treated with fertilisers);
- Land-use change: deforestation to create pastures or cultivated land to produce animal feed releases CO_2;
- Transport and processing: the transport of food, live animals, and processed products contributes to CO_2 emissions.

4.2.6 Map of Emissions from Farm Gate Productions

The emissions from the agri-food sector refer to three different categories: emissions emitted at the plot level (farm gate), emissions related to land-use change, and emissions related to pre-production and post-production activities. The map presented here (Map 4.8) focuses only on the emissions produced at the pre-production and post-production stages between 1990 and 2021. The pre-harvest stages refer notably to the production of fertilisers and irrigation, and the post-harvest stages to the following five categories: transport, processing, distribution, consumption, and finally waste management. As a reminder, Tubiello's (2022) study shows that since 2019, pre-production and post-production processes have surpassed farm processes to become the largest component of GHG emissions from agri-food systems, as confirmed by Map 4.8. The leading country in terms of agricultural GHG emissions at the plot level is China. A second group of countries includes major agricultural producers such as North America (United States and Canada), major European agricultural countries (France, Germany, Poland), Brazil and Argentina, and part of Asia (India, Indonesia), Russia and, more surprisingly, Sudan and Ethiopia (mainly due to agricultural methane emissions related to livestock).

4.2.7 Emissions from the Agri-Food Sector

The proposed map (Map 4.9) is based on the same sectors as Map 4.8 and focuses only on the emissions produced at the pre-production and post-production stages emitted between 1990 and 2021. As a reminder, since 2019, emissions during the pre-production and post-production stages have now surpassed emissions at the farm level (Tubiello et al. 2022), as confirmed by the map below. This shows that, as with emissions produced at the plot level, China and the United States are the leading producers of GHGs at the pre-production and post-production stages. A second group of countries includes most European countries (more countries than when only considering emissions at the plot level), which is mainly due to the transport of agricultural products. Brazil and Australia also belong to this second group, as well as a large part of Asia and Russia. In Africa, only Nigeria is part of this second group.

4.2.8 GHG Emissions Related to Land Use Change

By land use change, we refer here to the burning of forest biomass and the conversion of forest lands (into agricultural lands in particular). Between 1990 and 2021, we observe here (Map 4.10) that nearly half of the emissions related to land use change originate from the Americas, and substantially from Latin America, due notably to deforestation in the Amazon basin. Emissions induced by land use change are also high in Asia (21.6%) and in Africa (27%), also due to deforestation in Central Africa and Southeast Asia, particularly in Indonesia. The period studied (1990–2021) explains why Europe is an exception with emissions related to land use change, as the emissions related to land use change date mainly from the nineteenth and twentieth centuries.

4.3 Map of the Impacts of Climate Change on the Land Sector

Vincent Blanfort, Marie Hrabanski, and Julien Demenois

This map (Map 4.11) was established based on the IPCC synthesis report published in 2023 (AR6). It covers:

- the expected impacts of climate change in 2050 on agricultural, forestry and fishery productivity (forestry sector, livestock, crops, fishing);
- climate vulnerability factors (coastal areas vulnerable to sea level rise and flooding, areas exposed to desertification and increased fire risks, etc.);
- and the vulnerability of coastal populations (regions with high population density and cities threatened by rising waters).

The map unsurprisingly highlights the extent of the impacts of climate change on agricultural productivity and the increasing vulnerabilities to climate change in many areas of the planet.

More specifically, what stands out first when reading this map is the projected decline in productivity in both livestock and crop sectors across many areas and on every continent. However, some regions are also expected to benefit, with increases in crop productivity anticipated in the north-western United States, north-western Brazil, Namibia, Peru, Bolivia, and eastern Russia. As for livestock, productivity gains are expected in the central United States and Central Europe.

The situation for fisheries is much more geographically contrasted. A rise in fishery productivity is projected across the fishing grounds north of the Arctic Circle, while decreases are expected in temperate and tropical zones, particularly in Europe, along the west coast of Africa, in the Oceanian basin, and in the temperate Pacific region. Forest productivity, meanwhile, is expected to increase in Central Africa, the Amazon, Canada, and the Scandinavian countries, while a decline is projected in the eastern United States.

Beyond these initial observations, climate-related vulnerabilities are expected to multiply. Notably, there is likely to be an increase in the regions where tropical cyclones form, which will affect densely populated coastal areas. This concerns both the eastern and western coasts of the United States, as well as the waters off China, Japan, southern Africa, and the north-east of Australia. Wildfires are also expected to become more frequent across all continents, with the exception of Africa. Finally, drought- and desertification-prone areas are projected to expand.

4.4 Atlas of Land Carbon and Its Evolutions

Julien Demenois, Vincent Blanfort, and Marie Hrabanski

4.4.1 Map of Soil Organic Carbon Stocks

The soil is the largest terrestrial carbon reservoir: 2400 Gt of carbon between 0 and 2 m depth on a global scale (see Chap. 17). This stock is mainly found in the soil of forests (30%) and grasslands (30–35%), and to a lesser extent in the soil of croplands (15%). This is in addition to the carbon of permafrost (over 1600 Gt between 0 and 3 m depth).

The map of soil organic carbon stocks (SOC) between 0 and 30 cm depth is the result of the work of the Global Soil Partnership (GSOCmap, *global soil organic carbon map*). This map (Map 4.12) is the first global map of soil organic carbon ever produced in a consultative and participatory process involving member countries, making it absolutely new and unique. Maps 4.12, 4.13 and 4.14 can be viewed in digital and interactive version on the Impact4Soil platform (www.impact4soil.com) developed by Cirad and Vizzuality within the framework of the European ORCaSa project.

The highest SOC (Soil Organic Carbon) stocks are found in high or low latitude areas (above 40°) and in the intertropical zone. Ten countries hold more than 60% of these stocks, with Russia leading the way. Brazil, Indonesia, and the Democratic Republic of Congo are also on this list. *Conversely*, the dry regions of North Africa, the Middle East, or central Australia have lower SOC stocks.

4.4.2 Map of Past Changes in Soil Organic Carbon Stocks

Land use changes are a major source of net GHG emissions. Thus, the conversion of natural ecosystems into agricultural land has resulted in a cumulative loss of 116 Gt of carbon in the top two metres of soil since the Neolithic era (see Chap. 17).

The map of past changes in SOC stocks between 0 and 30 cm depth (Map 4.13) is based on the analysis by Sanderman et al. (2017). It shows the differences in SOC stocks between historical levels (−12,000 years) and current levels. This map is a statistical representation of the amount of soil organic carbon that may have been lost due to agriculture. It is a global product derived at a resolution of about 10 km.

The losses of SOC stocks (shown in red on the map) have been highest in Europe, the United States, and China. *Conversely*, some regions have seen their SOC stocks increase (shown in green on the map), notably in southern Mongolia or in the Nile delta.

4.4.3 Map of Future Changes in Soil Organic Carbon Stocks

Regarding climate regulation, carbon sequestration in soils, through an increase in SOC stocks, would represent 47% of the mitigation potential of agriculture and grasslands (see Chap. 17).

Using the IPCC's Level 1 accounting approach[1], the map of future changes in SOC stocks (Map 4.14) allows visualising the differences in SOC stocks between 2018 and 2038 between 0 and 30 cm depth, if land restoration practices for cultivated lands and grasslands were implemented. The IPCC's Level 1 accounting approach uses average regional response functions to estimate changes in soil organic carbon due to changes in land use. As such, this approach does not take into account smaller scale variations in the evolution of soil organic carbon, which will likely be observed depending on local soil types, local climate, and the local implementation of specific management strategies. The map does not take into account

[1] IPCC Glossary: "A level represents a degree of methodological complexity. Generally, three levels are proposed. Level 1 is the basic method, level 2 is intermediate, and level 3 is the most demanding in terms of complexity and data requirements." https://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_02_Glossary.pdf.

local feasibility or current adoption rates. This analysis is based on the assumption of instant adoption on all lands, even though in reality, the change will occur gradually over time.

This map highlights the significant potential for increasing SOC stocks (shown in green on the map), particularly in South America, Africa, and Southeast Asia, thanks to the restoration of cultivated lands and grasslands.

4.4.4 Current Carbon Stock of Above-Ground Biomass

The carbon stocks of terrestrial lands are mainly found in soils and in shrub and tree vegetation. Forests cover the planet over 3900 Mha (million hectares) and represent around 860 Gt of carbon (Gt: billion tonnes), of which more than 40% is in living biomass (see Chap. 9). The tropical forest represents more than half of the stocks. Forests, therefore, play a crucial role in climate change.

The map of above-ground biomass stocks (Map 4.15) represents the carbon stocks in above-ground biomass, which is on average composed of 50% carbon. This map is based on the methodology presented in Baccini et al. (2012) to generate a global map of the density of living woody above-ground biomass at a resolution of about 30 m for the year 2000. The map can be viewed in digital and interactive form on the Global Forest Watch platform (www.globalforestwatch.org).

The three major tropical forest masses, namely the Amazon, Central Africa, and the Borneo-Mekong basin, hold the majority of these above-ground biomass stocks.

4.4.5 Current Net GHG Fluxes at the Forest Level

Forests are the main carbon sink in terrestrial environments, the second sink after the oceans. They, therefore, play a crucial role in climate change. They would capture, according to the estimates, between 70% and 100% of the carbon annually captured by the emerged lands (1.8 Gt of carbon per year) (see Chap. 9).

The map of current net GHG fluxes in forests (Map 4.16) shows the difference between the carbon emitted by forests and the carbon absorbed by forests between 2001 and 2023. Negative values (in green on the map) correspond to net carbon sinks and positive values (in purple on the map) to net carbon sources. Net fluxes are calculated based on the IPCC guidelines for national greenhouse gas inventories. The map can be viewed in digital and interactive format on the Global Forest Watch platform (www.globalforestwatch.org).

This map clearly highlights GHG emissions due to deforestation and forest degradation in North America (particularly due to mega-fires), in the Amazon, and in Indonesia. Conversely, GHG absorptions by forests in Europe and China are noticeable.

4.4.6 The Potential for GHG Sequestration in Forests

Forests could store 226 Gt of carbon in addition to the current stocks, if regenerated. Such restoration could be implemented in areas often on the fringes of large tropical forest masses, which are no longer used for agriculture and remain free from urbanisation (see Chap. 9).

The map of the potential for GHG sequestration in forests (Map 4.17) displays the rate at which forests could capture carbon from the atmosphere and store it in above-ground living biomass over the first 30 years of natural forest regrowth. These rates are presented for reforestable areas and exclude areas of grasslands and indigenous crops in order to preserve food and fibre production as well as biodiversity habitat. The map can be viewed in digital and interactive format on the Global Forest Watch platform (www.globalforestwatch.org).

This map highlights the importance of this potential in Central America and the Caribbean, as well as in South America, Southeast Asia, and Europe. On the other hand, the potential appears more limited in Africa, with the exception of West Africa.

4.5 Changes and Impacts of Climate Change by Major Region on the Land Sector

4.5.1 The Anticipated Climate Changes and Impacts in Africa

Nicolas Viovy, Jacques André Ndione, Moussa Waongo, and Maguette Kaire

4.5.1.1 The Anticipated Climate Changes in Africa

Temperature

As with all continents, the temperature in Africa will increase, but less strongly, on average, than on the Eurasian and North American continents. Moreover, climate change will affect the different African regions unevenly: in the high latitudes, the temperature increase will be greater than in the tropical zones, with the exception of the Sahel (Fig. 4.4). Consequently, this increase (of about 0.8 °C) will be more significant in the north and south of the continent than in the equatorial zone. However, as the temperature is already high, particularly in the savannah and semi-desert areas, many regions will reach temperature peaks above 50 °C, a critical threshold for humans and all species.

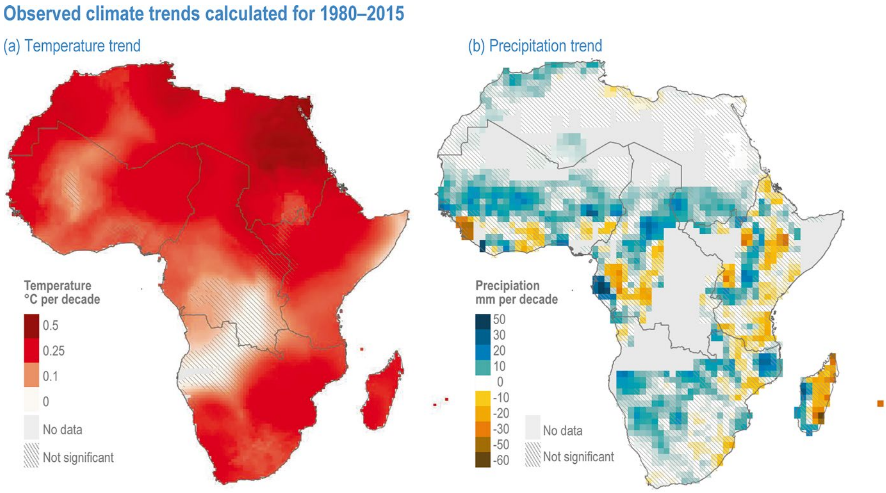


Fig. 4.4 Trends in temperature and precipitation changes over the last few decades (1980–2015) in Africa (**a**) Températures (**b**) Précipitations. (Source: IPCC AR6 (2022))

Precipitation

The uncertainty about the evolution of precipitation in Africa is significant. Projections indicate strong contrasts with a drying of the entire Mediterranean rim as well as part of the Atlantic coast and throughout the south of the continent (Fig. 4.4). On the other hand, the rest of the continent should see its precipitation increase. Unlike other regions, such as India, the duration of the monsoon period should not vary significantly. Interannual variability should increase leading to both an increase in episodes of intense precipitation, but also periods of drought during the rainy season. These effects could unfortunately offset the positive effect of the average increase in precipitation over part of the continent.

Winds

As in the entire tropical zone, if there is no clear trend on the change in the frequency of cyclones (which could even decrease slightly), their intensity has, however, increased and should continue to grow in the future. This phenomenon is linked to the increase in the temperature of the oceans and the atmosphere, which is becoming more humid.

Sea Level

As with the rest of the globe, an increase in sea levels is expected, which will affect coastal areas. The rise in water levels will continue, even if we manage to stabilise atmospheric CO_2, the rise will continue on a long time after the CO_2 decrease. The sea level has risen by about 23 cm since 1880 and is expected to rise another 30 cm by 2050 (IPCC 2014). This effect, combined with the increase in the intensity of cyclones, raises concerns about risks increased submersion of certain heavily populated coastal regions (such as the Nile Delta, the city of Lagos in Nigeria or Dakar in Senegal).

4.5.1.2 The Impacts of Climate Change on Different Sectors of Agriculture in Africa

Climate change poses complex challenges for agriculture in Africa, requiring robust adaptation strategies to ensure the resilience of agricultural systems and food security. The increase in precipitation variability is a major problem, particularly in areas heavily dependent on the rainfall regime such as the Sahel (Box 4.2), Southern Africa and the Horn of Africa. On the one hand, the unpredictability of rainfall in some places complicates the planning of crop cycles, and late or irregular rains can lead to a decrease in yields or the total loss of some crops. On the other hand, the risk of prolonged droughts will increase and will have impacts on agricultural production. It should be noted that the increase in temperatures increases evapotranspiration and therefore the risk of agricultural drought. This increase also poses a direct risk to crops by reinforcing the risk of heat stress and therefore of yield decreases. Climate change also risks inducing an extension of diseases and pests affecting both crops and livestock. At the same time, extreme weather events such as torrential rains and droughts accelerate soil erosion and land degradation, reducing soil fertility and long-term agricultural production capacity. The increase in the irregularity of rainfall as well as the increase in agricultural commodity needs linked to that of the population (and a possible change in diet) increase the need for irrigation, which can exacerbate conflicts between farmers, livestock farmers and other water users, complicating the sustainable management of water resources. Finally, climate constraints sometimes force farmers to abandon traditional diversified crops in favour of more resistant crops or monocultures, which can reduce agricultural biodiversity and increase vulnerability to other threats, such as pests. These various risks are exacerbated by the fact that the majority of farmers in Africa are smallholders, often poor: their capacity (financial and technological) to adapt to the impacts of climate change is limited, which makes them particularly vulnerable.

Box 4.2 West Africa will be heavily affected by climate change

Currently representing only 1.8% of global greenhouse gas (GHG) emissions, the countries of the ECOWAS region (Economic Community of West African States) contribute very little to climate change. According to the most pessimistic scenarios, West Africa will experience, by 2060, a temperature increase of +2.3 °C, i.e. a warming of +0.6 °C per decade. Indeed, in West Africa, the number of potentially lethal heat days could reach 50 to 150 days per year for

(continued)

Box 4.2 (continued)

a climate warming of 1.6 °C and 100 to 250 days per year for a climate warming of 2.5 °C, with the strongest increases in coastal areas. Children born in West Africa in 2020 will, in the event of climate warming of 1.5 °C, be exposed to 4 to 6 times more heatwaves during their lifetime than those born in 1960. For the tropical zone of West Africa, the risk of heat-related mortality is 6 to 9 times higher than the average for the years 1950–2005 at 2 °C of climate warming. With increasing urbanisation, cities like Lagos, Niamey, Kano and Dakar are particularly exposed (Trisos et al. 2022). As for rainfall, it is expected to be more erratic and should lead to an increase in the frequency and intensity of extreme climate hazards already known in the region: floods, increased rainfall variability (translation of isohyets), pockets of extremely long drought, among other corollaries, with dramatic human (ecosystem degradation) and economic consequences on all economic sectors and on the most vulnerable populations, including women, young people and the elderly. Regarding the emblematic region of the Sahel, recent analyses on the current evolution of the climate show an even more acute intensification of extremes. The Droughts are becoming increasingly intense, as are floods, to the point that researchers are discussing the advent of a new climatic era (Panthou et al. 2018).

The consequences are already dramatic. In October 2022, heavy rains and floods killed hundreds of people, displaced thousands more, and destroyed over a million hectares of cultivated land in Niger, Mali, and Burkina Faso (UN News[2]). Compared to the period 1986–2005, a global warming of 3 °C is expected to reduce work capacity in agriculture by 30–50% in Sub-Saharan Africa, due to rising temperatures. Climate change has increased extreme poverty in the West Africa region by nearly 3% in 2021. Gender inequalities in the Sahel and West Africa are among the highest in the world. Multiple interconnected crises (climate, security, health, and food) exacerbate these inequalities and increase the vulnerability of women.

Regarding agricultural sectors, the livestock sector is particularly affected due to the decrease in water availability, a decline in biomass potential, degradation of pastures (Savadogo et al. 2011), and an increase in cases of thermal diseases. With a global warming of 1.5 °C, sorghum yields are expected to decrease in West Africa, and a 9% decrease in maize yields is expected (Fig. 4.5). For cocoa trees, which grow at optimal temperatures around 25 °C in West Africa, temperature increases will cause drastic drops in cocoa production by 2030 in Ghana and Ivory Coast.

[2] UN News Global perspective Human stories. https://news.un.org/en/story/2022/10/1129997.

[3] https://cordex.org/.

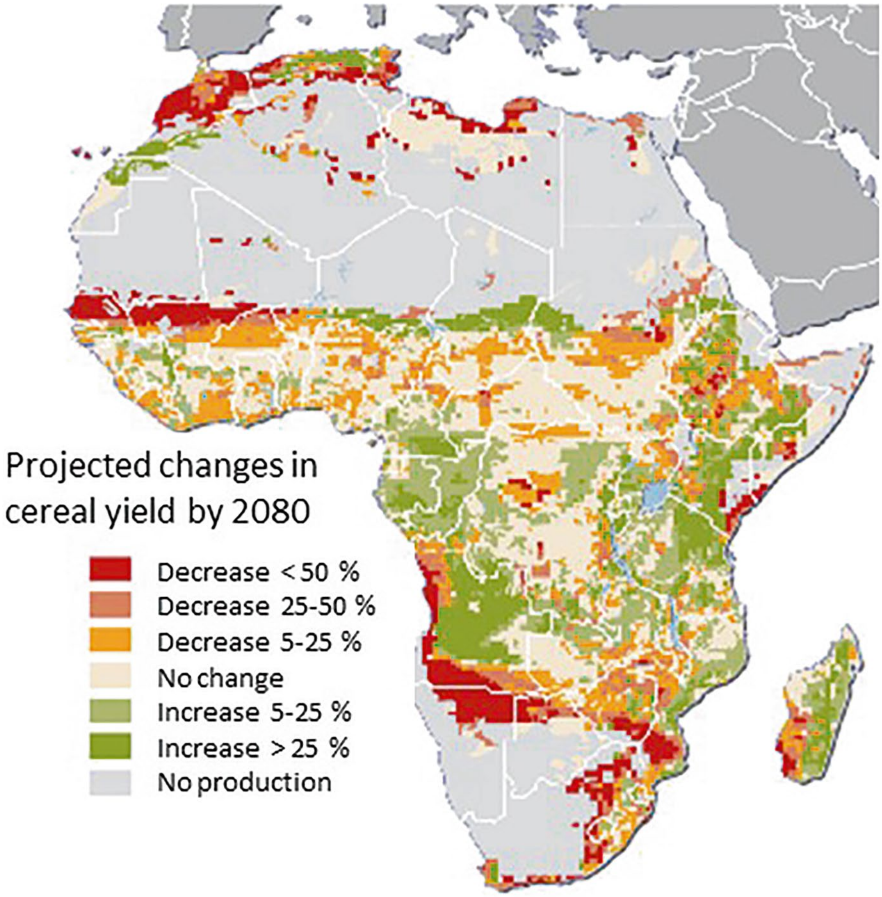


Fig. 4.5 Change in cereal yields by 2080 in Africa compared to the year 2000 in a high emission scenario (A2). (Source: Fisher et al. (2005))

4.5.1.3 Contribution of the Agricultural Sector to the Greenhouse Gas Balance

While Africa is one of the regions most vulnerable to climate change, the direct impact of its agriculture on GHG emissions is smaller than in developed regions (Fig. 4.6). Agriculture is indeed much less mechanised and uses less fertiliser, and the diet is less meat-based than in developed countries. However, if we take into

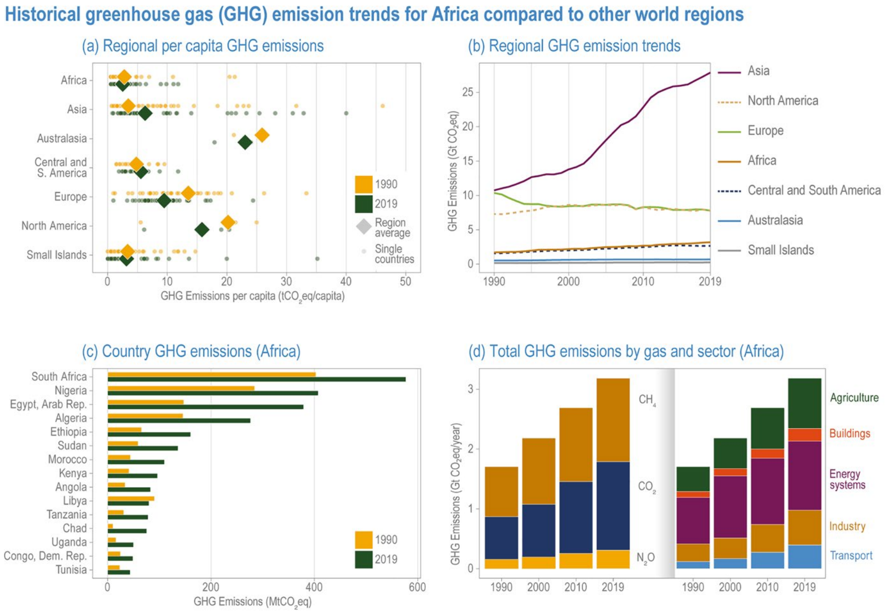


Fig. 4.6 Historical trends of greenhouse gas (GHG) emissions in Africa compared to other regions of the world (**a**) GHG emissions per person and by region, and their evolution from 1990 to 2019 (circles represent countries, diamonds represent the regional average); (**b**) Total GHG emissions by region since 1990; (**c**) Total GHG emissions in 1990 and 2019 for the fifteen highest emitting African countries; (**d**) Total emissions in Africa since 1990, broken down by GHG (on the left) and by sector (on the right). Methane and CO_2 emissions represent an almost equal share of GHG emissions in Africa, with the most significant emission sectors being energy and agriculture (Crippa et al. 2021). Agriculture emissions in panel (**d**) do not include land use, land-use change, and forestry (LULUCF CO_2). The global warming potentials over one hundred ans, in line with the estimates of Working Group I (WGI), are used. The emission data comes from Crippa et al. (2021), compiled in Chap. 2 of Working Group III (WGIII) of the IPCC's AR6

account the impact related to land use change, mainly due to deforestation, the GHG emission balance becomes much more significant and then represents 22% of global AFOLU sector GHG emissions (Brouziyne et al. 2023). The impact of land use change in Africa then accounts for half of GHG emissions. Similarly, the trend is towards an increase in emissions, rising from 1.8 Gt CO_2 eq in 2000 to 2.2 Gt CO_2 eq in 2018 (FAO 2020).

Box 4.3 The North Africa and Middle East region: a hotspot for climate change

The North Africa—Middle East (MENA) region is both a particularly high emitter of GHGs (in 2018, this region produced 8.7% of GHGs, while it only represented 6% of the world's population) and a region particularly vulnerable to the effects of climate change. It includes both high-income oil-exporting countries in the Persian Gulf area, middle-income countries (Morocco, Turkey, Egypt, etc.), and some of the least developed countries such as Sudan, Yemen, and Mauritania.

Climate change will indeed exert increasing pressure on the already scarce water and agricultural resources in the MENA region, thus threatening national security and the political stability of the entire region. The temperature increase observed in this region has been almost twice as fast as the global average. In addition to heatwaves, which are expected to be more intense and frequent, regions adjacent to the Mediterranean Sea should experience a decrease in rainfall ranging from 20% to 40%. Droughts are expected to last up to 90% longer. The region is also particularly sensitive to the phenomenon of desertification. Egypt, Jordan, and Palestine are already experiencing a decline in their vegetation, up to 80% of their land areas. In addition to increasing the aridity of the region, disrupting agricultural patterns, this phenomenon should also increase the number and intensity of sandstorms. In this part of the world, which already houses twelve of the seventeen countries most affected by water scarcity, and where the population is set to double by 2050, the consequences of the climate crisis on societies should be considerable. The consequences for agriculture will be major, as the IPCC estimates that nearly 45% of agricultural land should be exposed to salinity, soil nutrient depletion, and erosion. At the same time, this region heavily depends on imports of agricultural products: 40% of its food needs are currently covered by imports, and climate change should further accentuate this trend.

The continuation of the *status quo* will lead to an additional average regional warming that could reach 5 °C by the end of this century, thus risking making part of the MENA region uninhabitable, even though not all countries are equally affected by the impacts of climate change.

4.5.2 The Projected Climate Changes and Impacts in Southeast Asia

Alain Rival

4.5.2.1 The Climate Changes in Southeast Asia

Archipelagic by nature, Southeast Asian countries experience strong land-ocean-atmosphere interactions. The climate is predominantly tropical, warm and humid with abundant rainfall. The seasonal variability of precipitation in the region is primarily influenced by monsoon systems, the north-south migration of the intertropical convergence zone, and tropical cyclones (mainly for the Philippines and Indochina). Southeast Asia (SEA) proves to be one of the world's most vulnerable regions to climate change due to its extensive coastlines, heavy reliance on agriculture and forestry, and more generally on natural resources, including minerals. Each year, torrential monsoon rains and several cyclones cause hundreds of deaths in Southeast Asia (and affect millions of people); they also contribute to the rise in the price of rice and foodstuffs.

Southeast Asia is home to a significant concentration of countries heavily affected by climate change: four of the ten most affected countries in the world belong to this region, namely Myanmar, the Philippines, Thailand, and Vietnam. Indonesia has become the country with the highest GHG emission rate in the region in 2021, recording 2.05 billion tonnes. After Indonesia, Vietnam ranks second with 507.34 t, while Thailand ranks third with 452.12 Mt. Conversely, Timor-Leste has the lowest GHG emissions, at 9.38 Mt (Sonobe et al. 2024).

The region is facing increasing GHG emissions from agricultural sources: activities related to agriculture, forestry, and various land uses are essential for the region, for its food security, and for maintaining livelihoods in rural areas. These activities also significantly affect anthropogenic GHG emissions.

Deforestation is one of the main causes of GHG emissions from the agricultural sector. The massive conversion of land for agricultural purposes, especially for large-scale commercial agriculture including oil palm plantations, releases the carbon stored in trees and reduces the forests' ability to absorb CO_2.

The development of agricultural activities in Indonesia (Sonobe et al. 2024) has stimulated economic growth, but has also led to excessive ecological and economic costs. Between 2007 and 2018, this development generated about 48 billion dollars (5.7% of the gross domestic product, GDP), but air pollution and fires offset more than half of this amount. Measures to prevent fires and restore peatlands are now reducing these costs.

Highly exposed, being predominantly insular, and with low resilience, the region is vulnerable to the effects of climate change (IPCC 2022), with a foreseeable increase in the intensity and frequency of extreme climate-related events (floods and droughts). This radical change in seasonal precipitation patterns would have enormous repercussions on livelihoods, infrastructure, agricultural production, and the region's food security.

Temperature

The average temperature in Southeast Asia is expected to continue to rise during the XXI^e^ century. The projections of multi-model regional climate simulations given by the Coordinated Regional Climate Downscaling Experiment (Cordex-Sea) initiative show that the temperature increase on land would be between 3 °C and 5 °C by the end of the XXI^e^ century compared to the period before 1986–2005. For all levels of global warming (see Chap. 1), the land region is expected to warm slightly less than the global average.

Precipitation

The projections of future precipitation changes are very variable between the subregions of Southeast Asia and between the models (Fig. 4.7). Thus, the datasets provided by the Coupled Model Intercomparison Project (CMIP7) showed an increase in average annual precipitation over most land areas by the middle and end of the XXIe century, with a strong correlation to the model shown for higher warming levels only[3]. Based on the Cordex multi-model simulations for Southeast Asia, significant and robust increases in average precipitation over Indochina and the Philippines are projected, while a drying trend is noted over the maritime part for the early, middle, and end periods of the XXIe century.

By the end of the XXIe century, a 20% increase in average precipitation is expected in Myanmar, in north-central Thailand and northern Laos, and from 5% to 10% in the eastern Philippines and northern Vietnam. Significantly drier conditions are expected in other regions of Southeast Asia. In the Indonesian region, particularly on Java, Sumatra and Kalimantan, a decrease of 20–30% in average rainfall is expected by the end of the twenty-first century.

Fires

Nearly half of the world's tropical peatlands are located in Southeast Asia, where they constitute significant carbon reservoirs. Over the past three decades, most of the 25 Mha of tropical peatlands in the region have been deforested and drained. As a result, the lowering of the water table exposes the peat to oxidation, transforming the plant material accumulated over millennia into carbon dioxide and causing land subsidence. Nearly 80% of the region's natural peatlands have been deforested and drained, the majority of them are now occupied by perennial, forestry or agricultural plantations. This conversion increases the oxidation of the peat, which contributes to a rapid loss of carbon into the atmosphere in the form of greenhouse gas emissions, and increases their vulnerability to fires that regularly generate haze, with serious impacts on human health (Mishra et al. 2021).

Forest and vegetation fires, used as tools for agricultural expansion, are a major source of air pollution and can cause serious health problems in many regions of Southeast Asia. The economic cost of the forest fires that ravaged Indonesia during the El Niño episode of 2015 was estimated at over 16 billion US dollars, with over 100,000 premature deaths. For several days, the fires emitted more carbon dioxide in the region than the entire economy of the United States of America.

[4] Area of 462,840 km² for Papua New Guinea, and 20 km² for Nauru.

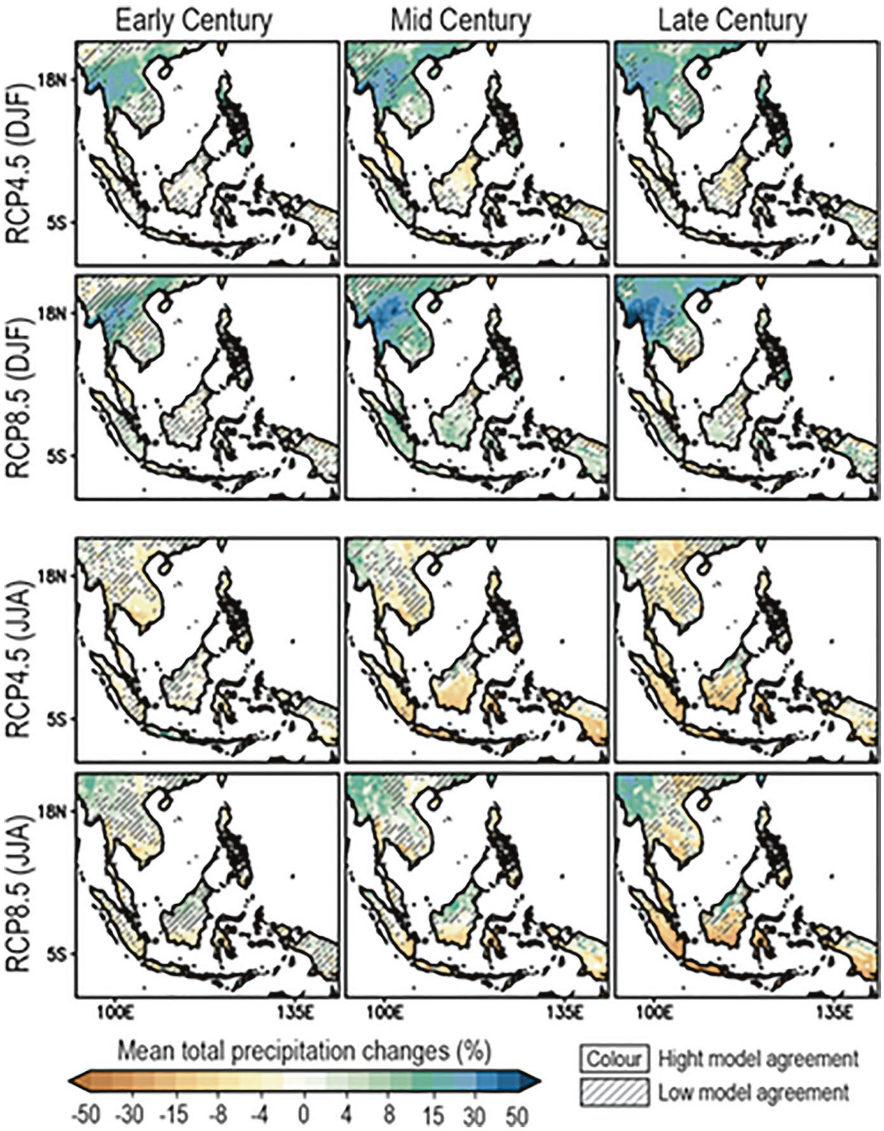


Fig. 4.7 Projection of expected changes through regional climate models (RCMs) for average rainfall between the beginning (2011–2040), middle (2041–2070) and end (2071–2099) of the twenty-first century and the historical period 1976–2005. (Source: Tangang et al. (2020); Fig. 10)) The data comes from Cordex-Sea downscaling simulations. The hatched lines indicate areas where model agreement is low (less than 80%). DJF: December-January-February; JJA: June-July-August.

Sea Levels

Changes in global sea level rise have undeniably begun to impact the island economies of Southeast Asia, which are already very vulnerable (Idris et al. 2023). Sea level rise can threaten the long-term sustainability of coastal communities and fragile ecosystems such as coral reefs, wetlands and mangroves. The Indo-Pacific region is home to most of the world's mangrove forests, although sediment input in this region is decreasing, due to the construction of dams on rivers.

Although the region tends to warm a little less than the global average, sea levels will rise faster elsewhere and shorelines will recede in coastal areas where 450 million people live. The rise in water levels is expected to cost billions of dollars in damage to major Asian cities during the current decade, and its impact is amplified by the tectonic movements of the fire belt and by the effects of massive groundwater pumping. Thus, nineteen of the twenty-five cities most exposed to a one-metre rise in sea level are located in Asia, seven of which are in the Philippines alone.

The coastal areas of Southeast Asia are densely populated and support a wide range of economic activities. The physical impact of sea level rise is manifested by coastal erosion and flooding of the lowest areas, salt intrusion, flooding due to storm surges and high tides as well as habitat loss. The economic impact of sea level rise results in the destruction of natural areas, fields and homes along the coasts, changes in land use, water management systems, navigation and waste management in coastal areas.

4.5.2.2 The Impacts of Climate Change on Different Sectors of Agriculture and Forestry in Southeast Asia

Agriculture and Forestry in Southeast Asia

The latest report from the Association of Southeast Asian Nations (ASEAN) on the state of climate change (ASEAN 2021) suggests that adaptation and mitigation actions should be synergistically implemented on the ground. Various examples include climate-smart agriculture and nature-based solutions, incorporating ecosystem-based adaptation such as agroforestry, protection of mangrove forests, and strengthening forest management through certification and reducing emissions from deforestation and forest degradation (REDD+) (see Chap. 6). Proper management of reservoirs for hydroelectricity will also protect local communities from river flooding and other extreme events, while contributing to climate change mitigation.

The IPCC report predicts particularly severe consequences for Southeast Asia, one of the most vulnerable regions of the planet to climate change. The regional bloc, primarily archipelagic, will be directly hit by rising sea levels, heatwaves, drought, and more intense and frequent rainfall episodes. Known as "rain bombs", episodes of heavy rainfall will intensify by 7% for each degree of global warming.

Biodiversity and ecosystem services play a crucial role in the socio-economic development as well as the cultural and spiritual fulfilment of the Asian population.

Species richness peaks in the Coral Triangle of Southeast Asia (Philippines and Indonesia), and the extent of mangrove forests in Asia accounts for about 38.7% of the global total. These coastal ecosystems provide multiple ecosystem services related to food production through fishing and aquaculture, carbon sequestration, coastal protection, and tourism and recreation.

Figure 4.8 schematically represents the expected impacts of climate change in some Southeast Asian countries. It clearly illustrates the spatio-temporal diversity of future impacts on food production, highlighting that there are “winners” and “losers” associated with climate change at different scales. The region’s food security remains heavily dependent on rice production, which shows significant vulnerability, particularly in Vietnam and Thailand. Other scenarios, on the other hand, predict an increase in yields due to climate change, due to an increase in rice productivity per hectare.

Data on the observed effects of climate change on agriculture and food systems in Southeast Asia remain scarce. Most impacts have been associated with drought, monsoon, and oceanic oscillations, whose frequency and severity have been linked and associated by several authors with climate change. Generally, the major consequences on agricultural production, as observed by farmers in the Philippines and Indonesia, mainly concern delays in harvest dates, decrease in yields and product quality, increase in pest and disease incidence, growth delays, increased livestock mortality, and a drop in agricultural income.

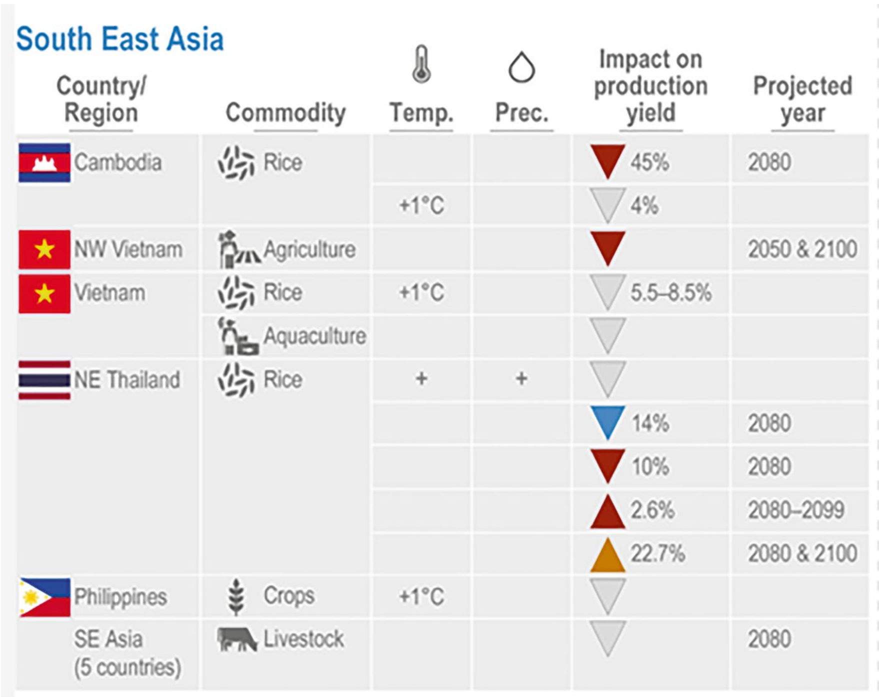


Fig. 4.8 Projection of the impacts of climate change on agriculture and food systems in the subregions of Asia, following the AR5 of the IPCC. (Source: Shaw *et al.* (2022; Fig. 10.6))

In most Southeast Asian countries, fisheries are small-scale activities, which are more vulnerable to the impacts of climate change than commercial sectors, with a general trend towards a decrease in the number of small units. The analysis of fishing-related activities shows a continuous decrease in catches, which will impact the future of the fisheries sector in the Philippines, Thailand, Malaysia, and Indonesia. Climate change is expected to reduce the overall production potential of fisheries due to a temperature increase of about 2 °C by 2050.

Just like fisheries, Asian aquaculture is highly vulnerable to climate change. The majority of shrimp farmers have observed that weather conditions have changed abruptly over the past five years and that high temperatures are the most damaging because they reduce growth rates, increase susceptibility to diseases, and affect farm productivity. Shrimp farms are also affected by changes in the variability and intensity of rainfall, perceived by the majority of farmers as part of the impacts of climate change. In Vietnam, small farmers are vulnerable to climate change: those who practice a type of extensive farming with few inputs are more fragile than those who follow a more intensive model, supported by more capital investments. Marine heatwaves pose a new threat to fishing and aquaculture, particularly in terms of disease spread. In the countries of Asia In Southeast Asia, it is predicted that over 30% of aquaculture zones will become unsuitable for production by 2050–2070, and that aquaculture production will decrease by 10–20% by 2050–2070 due to climate change.

Southeast Asia is home to nearly 15% of the world's tropical forests and includes at least four of the twenty-five global biodiversity hotspots. The region is also one of the main culprits for the disappearance of low-altitude and humid tropical forests. Thus, between 1990 and 2010, Southeast Asia recorded an average net loss of 1.6 Mha/year (0.6% per year), reducing the region's forest cover from 268 Mha to 236 Mha. Given these rates and the fact that over 90% of Southeast Asia's forests were still unprotected in the early 2010s, it is feared that more than 40% of the region's biodiversity may disappear by 2100 (Estoque et al. 2019).

A large number of published studies concern the predicted impacts of climate change on the production and economy of major crops: rice, maize, and wheat being the ones receiving the most attention. Climate change has, and will continue to have, a significant impact on agricultural production in various ways across Asia. An increasing number of sub-regional and regional studies using multiple modelling tools have provided significant evidence of the predicted impact of climate change on plant production, with clear indications of winners and losers depending on the countries concerned (Fig. 4.8).

While it is generally accepted that CO_2 promotes plant growth and productivity through the intensification of photosynthesis, uncertainty remains as to the extent to which carbon fertilisation will influence agricultural production in Asia. Indeed, plant nutrition is sensitive to rising temperatures, changes in water availability, and different adaptation measures employed in the field. The available literature indicates a clear trend towards the deterioration of grain quality and therefore a lower commercial value for rice grown in a high CO_2 environment. As global warming continues beyond 1.5 °C, the likelihood of negative impacts on agricultural and food security in many developing Asian regions will increase. There is a growing trend towards more integrated studies and modelling, which combine biophysical and socio-economic variables (including management practices) in a changing climate context, in order to reduce the uncertainty associated with future climate change impacts on the agricultural sector.

4.5.3 The Anticipated Climate Changes and Impacts in Central and South America

Lilian Blanc and Sylvain Schmitt

4.5.3.1 The Climate Changes in Central and South America

Central and South America are already experiencing the effects of global warming with an increase in cyclones, hurricanes, floods, droughts, sea-level rise, or the disappearance of glaciers. Beyond the social consequences (notably migratory movements), climate change also affects the supply of drinking water, food production (agriculture and livestock), and the natural ecosystems of this region, which contain 40% of the world's biodiversity and 25% of the world's forests. For this region, climate change amplify the net greenhouse gas emissions from the agriculture, forestry, and land-use change sectors, which are responsible for 25.3% and 20% of emissions respectively (Climate Watch 2022).

Temperature

In Central and South America, the increase in the greenhouse effect leads to a rise in average temperatures and average maximum temperatures of 2 °C to 6 °C depending on the regions and climate scenarios (Figs. 4.9 and 4.10), and a decrease in extreme low temperatures. The IPCC projects with certainty that these changes will affect all sub-regions of the continent with high to very high confidence. Moreover, the region currently has rates of temperature increase higher than the global average, an increase that is expected to continue in the future. This is a phenomenon with high confidence that affects (or will affect) all sub-regions of the continent.

Precipitation

The changes in precipitation in this region are less certain, but many studies predict increases in the northwest of South America and the Southeast, while decreases are expected in the Northeast and Southwest with very variable rates depending on the scenarios. These results are consistent for the end of the twenty-first century with the most intense increase scenarios (Fig. 4.9). Beyond trends, an increase in the

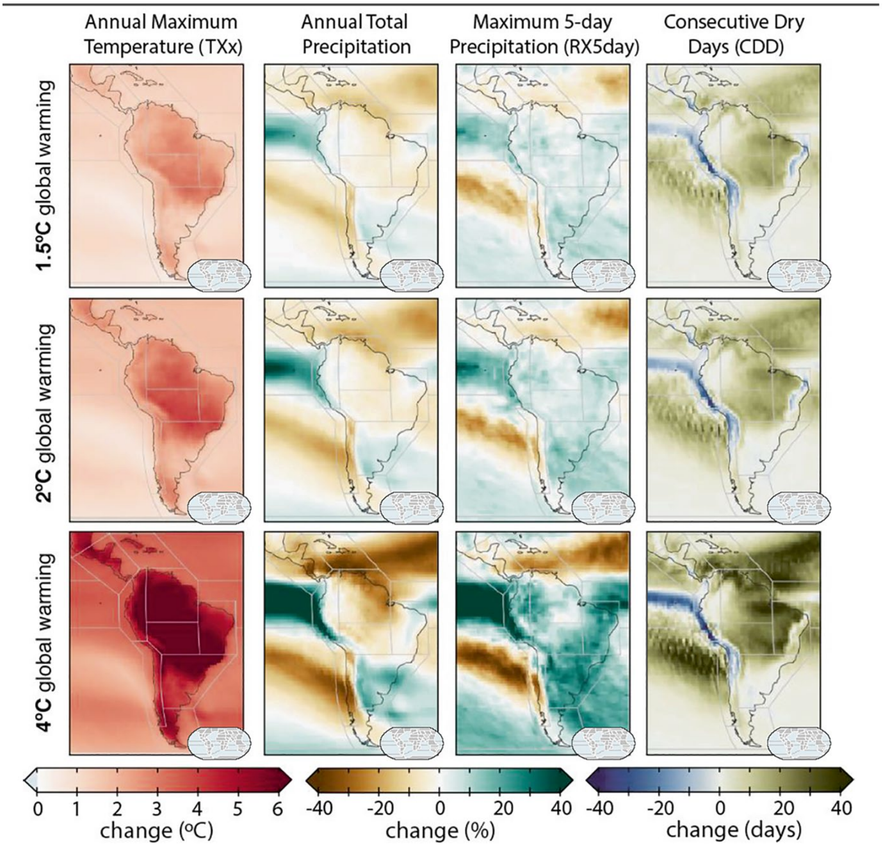


Fig. 4.9 Change in annual maximum temperature averages and precipitation in South and Central America under three global warming scenarios: +1.5 °C, +2 °C, and +4 °C compared to the 1850–1900 period. (Source: IPPC AR6 (2022))
The results are based on simulations from the CMIP6 multi-model ensemble (32 global models), using the SSP5–8.5 scenario to calculate warming levels.

intensity and frequency of extreme precipitation and floods is predicted in the north, northeast, southeast, and south of South America if the global temperature increase exceeds 2 °C (Fig. 4.9). These precipitations extremes lead to severe flooding and landslides. Conversely, in these regions, the number and frequency of dry days and droughts are also likely to increase. Southern Central America, and the south and southwest of South America are even expected to experience an increase in agricultural and ecological droughts by the mid twenty-first century . Finally, in the Andes, the loss of glacier volume and the thawing of permafrost will very likely continue under all IPCC scenarios, leading to large-scale glacial flooding and the overflow of glacial lakes.

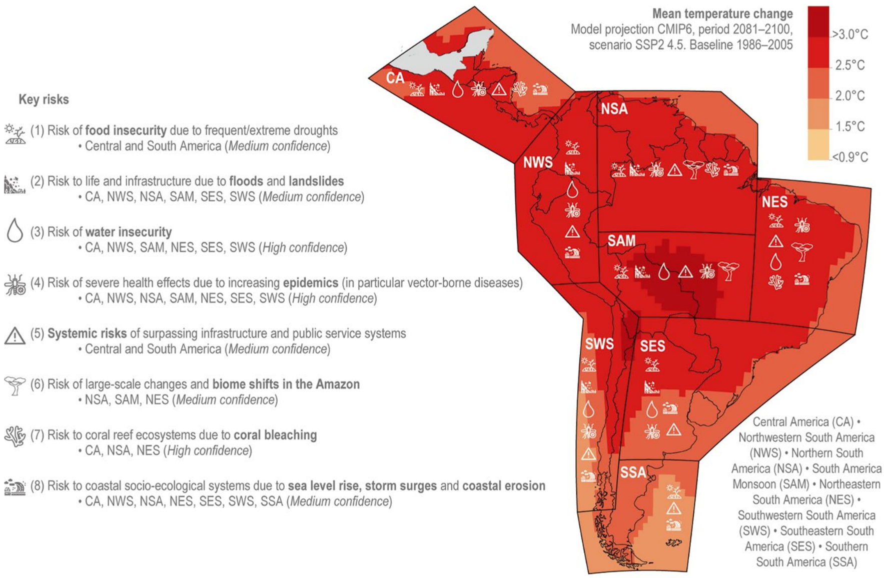


Fig. 4.10 Synthesis of the main risks related to climate change for South and Central America. (Source: IPPC AR6 (2022))
The base map indicates the average temperature change between the SSP2–4.5 scenario using the CMIP6 model projections for 2081–2100 and a reference period of 1986–2015.

Fires

The rise in temperatures, aridity, and more intense drought episodes create weather conditions conducive to fires, which are more frequent and intense, as illustrated by the recent mega-fires that have affected the Amazon. These fire-prone weather conditions are expected to increase in southern Central America and southwestern South America. On average, the inhabitants of the region have been more exposed to a high risk of fire, between 1 and 26 additional days depending on the sub-region, for the years 2017–2020 compared to 2001–2004 (Romanello et al. 2021). This increase in fires and aridity will potentially impact a wide range of sectors (including agriculture, forestry, health, and ecosystems).

Sea Level

In addition to the higher than average global temperature rise in South America, the relative sea level has risen more rapidly than the global average in the South Atlantic and subtropical North Atlantic, and less rapidly in the Eastern Pacific. This rise is expected to continue with a high degree of certainty (Fig. 4.10), contributing to the increase in coastal flooding in low-lying areas and the retreat of the coastline along most sandy coasts.

4.5.3.2 The Impacts of Climate Change on Various Sectors of Agriculture and Forestry in Central and South America

This region plays a major role globally both for biodiversity conservation (particularly with marine and terrestrial ecosystems in the Amazon region) and for agriculture with the production of agricultural commodities (livestock, coffee, bananas, sugar, soybeans, corn, sugarcane). This region is also characterised by two major factors that make it particularly vulnerable to climate change. On the one hand, significant land use changes (deforestation in the Amazon region) form a positive feedback loop with climate change, accentuating its effects. On the other hand, the region is characterised by strong social (access to land, for example) and geographical (urban *vs* rural) inequalities, with a high percentage of the population living below the poverty line.

Climate change has had a significant impact on agricultural production sectors in most regions with the magnitude of precipitation changes, extreme temperatures, and the changes in the agricultural calendar. Agriculture, livestock farming, fishing, and food systems in general have experienced medium to high impacts from climate change. In all regions, reductions in the growing season of crops have been observed for wheat (winter and summer), rice, maize, and soybeans, between 1981 and 2019. This reduction amounts to 10% for rice in South-West America and 5% for maize in Central America. The reduction in growing periods decreases yields.

For the three production sectors (annual and perennial crops, and livestock), however, strong regional variabilities are observed. In the northeast of South America, dry spells, with high temperatures and a decrease in precipitation, have been damaging to these three agricultural sectors. Other regions have also been affected such as Central America, the southeast and southwest of South America (annual crops), and the extreme south of the continent (livestock). In the future, these three production sectors will be greatly affected in the northeast and northwest regions, and to a lesser extent in the Cerrado region (centre of the continent). In this region, the yields of soybeans and maize will suffer one of the strongest negative impacts according to the estimates of the RCP4.5 and RCP8.5 scenarios and will require high levels of investment in adaptation if they continue to be grown in the same areas as currently (high confidence).

In Central America and the Andean foothills, annual crops will also be greatly affected. These effects are expected to worsen the situation for small and medium farmers and for indigenous populations in the mountainous areas of these regions. Under the A2 scenario (future with high GHG emissions leading to warming of 3.2 to 5.4 °C with regionalised economic growth and a strong increase in population), yield reductions in 2050 are estimated at 19% (beans) and between 4% to 21% (maize) for Central America. Food security in these two regions will therefore be largely compromised (high confidence).

The Amazon rainforest, one of the world's largest reservoirs of biodiversity and carbon, has already been and will continue to be highly vulnerable to drought (high degree of confidence). The Amazon rainforest has thus been heavily affected by the unprecedented droughts and high temperatures observed in 1998, 2005, 2010 and

2015/2016, which are partly attributed to climate change, causing an excess mortality of trees. The consequences of these strong climatic anomalies are an excess mortality of trees and a reduction in forest productivity at the basin scale. These strong changes in the functioning of forests temporarily transform forests from carbon sinks to carbon sources (high confidence). In addition, the combined effect of deforestation causing a change in land use, forest degradation (Bourgoin et al. 2024; Le Roux et al. 2022) and climate change increases the vulnerability of these terrestrial ecosystems to extreme climatic events (Phillips et al. 2009; Bennett et al. 2023). With these changes, the probability of transition, i.e. a transition from the tropical forest to other forest systems (seasonal forest) or savannah-like systems, is now assessed with a medium degree of confidence.

4.5.4 The Projected Climate Changes and Impacts in the Small States and Island Territories of Oceania

Séverine Bouard, Catherine Sabinot, Pierre-François Duyck, Philippe Birnbaum, Audrey Leopold, Julien Drouin, Fabian Carriconde, Laurent L'Huillier, and Christophe Menkès

4.5.4.1 An Uncertain Balance in the Face of Climate Change

The territories and countries of Oceania present a great diversity in terms of geography, geological history, size, topography, and local climatic conditions. However, this diversity, which gives rise to a unique cultural, biological, and food richness, also exposes them to a high vulnerability to climatic hazards. A single cyclone, a year of drought, or a biological invasion can wipe out the agricultural production of an entire country and eradicate numerous endemic species.

Very distant from each other, they have very variable sizes[4], leading Hau'ofa to name the region "our sea of islands" (Hau'ofa 2013) (Fig. 4.11). Located in a geologically very active region of the world, these archipelagos have complex geological histories, leading to a consequent diversity of their geological and pedological substrates. The Melanesian countries are rather large and mountainous, rich in mineral resources, while the Polynesian and Micronesian islands range from small volcanic islands to coral atolls. These islands have a great diversity of terrestrial and reef ecosystems, hosting a very rich biodiversity, a source of food for the communities.

If the island countries of the Pacific only represented 0.06% of the total carbon dioxide emissions in the world in 2019[5], they are particularly affected by climate change, even questioning their existence, as some are threatened with submersion (notably Kiribati, Tuvalu and the Marshall Islands).

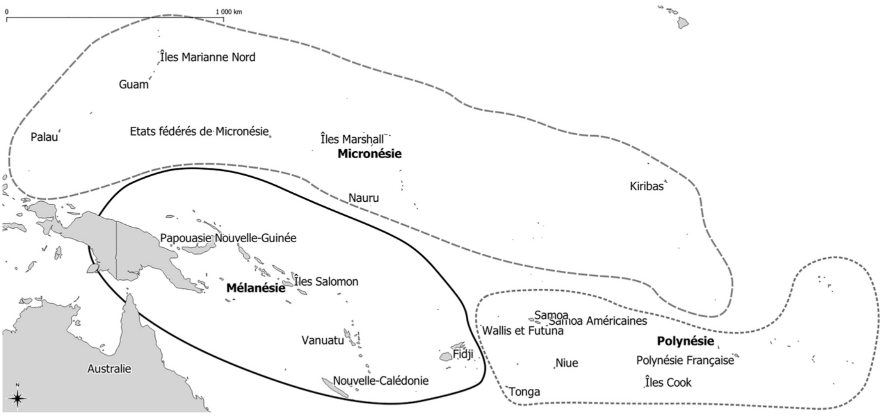


Fig. 4.11 The three major sub-regions of the South Pacific islands. (Source: map created by Jonas Brouillon, New Caledonian Agronomic Institute (IAC))

4.5.4.2 Insularity, a Geographical Challenge that Complicates Climate Projections

In this "ocean of islands", the most probable future scenarios are between SSP2–4.5 and SSP3–7.0 (IPCC 2022). However, the global climate models used in the Pacific and employed in the IPCC reports present numerous biases and uncertainties, particularly concerning the uncertain simulations of the South Pacific Convergence Zone (SPCZ) (Brown et al. 2020) regardless of the scenarios (Fig. 4.12).

These uncertainties have repercussions on the future evaluation of climate events such as El Niño-Southern Oscillation (ENSO), cyclones, heatwaves, heavy rainfall and droughts. In the South Pacific, studies predict a trend towards a decrease in the number of cyclones (with low confidence, however) in the scenarios considered realistic, but without consensus on the intensity of future cyclonic winds of these phenomena. However, the intensity of cyclonic rainfall will increase (Dutheil et al. 2020, 2019; Walsh et al. 2012, 2020; Knutson et al. 2020). Regardless of the scenarios, the expected increase in the number of heatwaves, the duration of heatwaves and temperature records is almost certain (Power and Delage 2019), but remains difficult to quantify due to model biases. Indeed, the IPCC models do not take into account local phenomena resulting from the interaction with the complex topography of the islands, as their grid is too coarse, on the order of a hundred kilometers (Evans et al. 2024). These gaps compromise the ability to reliably estimate the future evolution of precipitation, droughts and heatwaves.

[5] Data from the World Bank Wallis and Futuna which does not appear in this database. With Australia and New Zealand, this figure rises to 1.3% in 2023 (https://data.worldbank.org/indicator/EN.GHG.ALL.MT.CE.AR5). The figures show the significant contribution of the mining sector to emissions. With 6.614 Mt of CO_2 for 270,000 inhabitants in New Caledonia versus 3.401 Mt of CO_2 for 918,000 inhabitants in Fiji (latest available data from 2023).

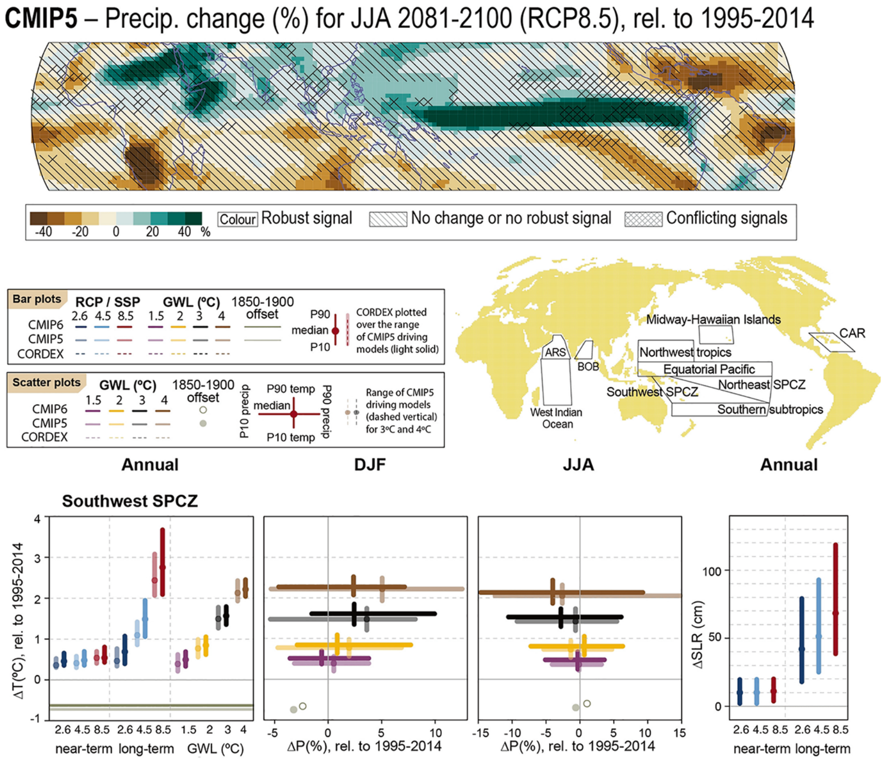


Fig. 4.12 Extract from the IPCC atlas for the SPCZ area
Top panel, expected average change (in %) of precipitation in the tropical Pacific, with hatched non- significant areas (including the SPCZ). Bottom panels: average changes in the annual average surface air temperature, precipitation and sea level rise relative to the 1995–2014 baseline in the Southwest SPCZ area. These changes are given annually or on a seasonal basis—December-January-February (DJF), June–July-August (JJA)—for the different scenarios (RCP/SSP), but also for warming levels (GWL: Global Warming Level), and for the CMIP6 and CMIP5 exercises (colours). The bars represent 90% of the distributions. (Source: IPCC (2021))

The few climate projections for the region, at a higher resolution, nevertheless indicate a general drying of the Central Pacific (Dutheil et al. 2020). Extreme rainfall events could increase in frequency from an occurrence every twenty years (period 1986–2005) to an event every ten, or even 4–6 years by 2090, according to certain greenhouse gas emission scenarios. Their intensity should increase. An increase of 0.5–1.3 °C in the average atmospheric temperature has been observed on the islands of the Western Pacific since the pre-industrial period (Whan et al. 2014). Depending on the emission scenarios, this increase in the average temperature could reach 2 °C to 3.7 °C by 2090 (Fig. 4.12). A sea-level rise of 20 cm to 120 cm by 2100 is projected according to scenarios, compared to the 1995–2014 averages (Fig. 4.12). The rise in sea level varies significantly between the archipelagos of the region. Importantly, this observed rise is not entirely attributable to changes in sea level due to climate change, as many Pacific islands also experience tectonic subsidence (Martínez-Asensio et al. 2019). Low-lying islands such as Kiribati, Tuvalu, and the Marshall Islands are already threatened with disappearance. The first bilateral treaty offering a migration path for Tuvaluans to Australia was signed in November 2023. In the Fiji Islands, a sea-level rise of nearly 5 mm per year is observed. This increase will thus heighten the risks of coastal flooding and intensify coastal erosion caused by cyclones, extreme distant swells, or tsunamis.

4.5.4.3 A Strong Climate Dependence of Ecosystems and Agrosystems

The Pacific encompasses five of the thirty-six "global biodiversity hotspots" and exhibits a high endemism of its biological resources. This is the result of the geographical isolation of these islands, the diversity of available habitats, and specific evolutionary processes. These territories host numerous remarkable plant and animal species found nowhere else (Payri and Vidal 2019). However, sea-level rise, extreme weather events, temperature changes, and changes in precipitation patterns threaten the specific habitats of these species.

A simulation based on nine climate change scenarios predicts that the distribution range of 87–96% of native and endemic tree species in New Caledonia will have decreased by 2070, that 52–84% of species will lose at least half of their current distribution range, and that 0–15% will disappear (Pouteau and Birnbaum 2016). Moreover, the intensive fragmentation of these ecosystems and the invasions of exotic species will disrupt the ecological balance in which these endemic species have developed. Climate change, in interaction with the increase in passenger flows and trade exchanges, changes the geographical distribution of pests and crop diseases, but also directly modifies their impacts (Bale et al. 2002; Hulme 2011).

The islands face multiple threats to their terrestrial resources (Nurse et al. 2014; Wong et al. 2014) and particularly to their soils. The effects of temperature increases are multiple and can affect their fertility and health (Filho et al. 2023). Soil organic matter (SOM) is crucial for soil fertility (see Chap. 17), but its stock can decrease with increasing temperatures which favour the mineralisation of SOM, affecting the water retention capacity of soils, their porosity, and can make them more susceptible to erosion. The intensification of rainfall events increases the disintegration, leaching (loss of nutrients) and acidification of soils, while droughts and sea-level rise increase salinity, reduce water availability and promote desertification. Climate change can also alter soil biodiversity. Thus, the soils of island territories, often naturally infertile (New Caledonia, Pillon et al. 2021) and with unique biodiversity (Carriconde et al. 2019), agricultural and forestry systems could be particularly transformed. While the soils of the region and their functioning remain largely unknown despite recent work on the subject (such as Carriconde et al. 2019; Demenois et al. 2020; Kulagowski et al. 2021; Léopold et al. 2021), limiting the effects of climate change on agroecosystems can be achieved by relying both on the knowledge already tested by the populations and on that brought by the scientific world. A dynamic of co-creation of knowledge will be essential to ensure sufficient resilience of agricultural productions.

4.5.4.4 Resilient Pacific Island Societies... But to What Extent?

The agricultural systems of the Pacific island states and territories are mainly based on family-type farming, with production primarily intended for local consumption. Staple food crops include yam, taro, sweet potato, cassava, bananas, tropical fruits, and vegetables. Cultivating these crops with contrasting water needs relies on techniques adapted to local conditions, different in Melanesia, Polynesia, and Micronesia. The indigenous knowledge associated with these practices is rich and diverse, but it is being undermined by transformations in lifestyles (migration and work reorganisation, etc.), with the reduction of available land and with the new climatic constraints and Environmental. The production systems in agriculture and livestock farming for the local market and export (kava, cocoa, spices, sugar cane, cattle, etc.) are also subject to the effects of climate change. Changes in the soil, the water demands of these systems, and pressures from pests and diseases jeopardise the financial resources of households that depend on them, as well as those of these countries with already unbalanced trade balances. Even capital investments that allow for a relative artificialisation of growing conditions (greenhouses, soil-less cultivation) are vulnerable to the most violent climatic events. As for livestock farming, efforts to tropicalise cattle herds, as in New Caledonia, could make these production systems relatively resilient, but the management of pastures, still unsophisticated, subject to the pressure of invasive plant species, and not agile in the face of the irregularity of the lengthening and intensification of droughts, will hardly achieve a production satisfying local needs.

Climate change will have significant repercussions on agricultural and food systems, with consequences for food security, health, and economic development (Barnett 2020; McCubbin et al. 2015; Klöck and Fink 2019). The intensification of floods and droughts has short-term consequences—natural disasters can destroy entire crops and decimate livestock—as well as long-term effects on food production. These phenomena also accelerate the loss of arable land already occurring in some areas due to coastal erosion, sea-level rise, and saltwater intrusion. Combined with the processes described above, the cultivated and cultivable areas are likely to decrease, as is the diversity of plants adapted to these new climates and environments.

However, the inhabitants of the Pacific archipelagos have different local experiences of the scientific vision of climate change (Fache et al. 2019). Environmental and social changes are perceived as very closely linked and must be addressed simultaneously (Pascht 2019). The inhabitants have already developed practices and diversification strategies to limit damage to their crops, to cope with losses, and to adapt to environmental constraints. Subsistence strategies based on multi-activity are particularly called upon after natural disasters (see Chap. 5). Turning to the lagoon and its fishing resources is common following the destruction of crops and allows for a new production cycle to be launched immediately after the event. However, the frequency of devastating events and the concomitant transformation of terrestrial, marine, and coral ecosystems significantly weaken the security offered by multi-activity. This raises questions about the risks, challenges, and resilience of these inhabitants in the face of intense climatic hazards and prompts us to question the local and global policies to be implemented[6].

The small states and island territories of the Pacific, often overlooked by the major states, while they record the most significant negative impacts of climate change, face an urgent and vital need for more research and data.

4.5.5 The Anticipated Climate Changes and Impacts in Europe

Nicolas Viovy

4.5.5.1 The Climate Changes in Europe

Temperature

The first effect directly linked to the greenhouse effect resulting from the increase in CO_2 in the atmosphere is the rise in temperatures. This is a phenomenon on which we have a high degree of certainty and which will affect the entire continent. The increase in temperatures is faster on continents than on the ocean, and faster in temperate and boreal zones than in the tropics, so this temperature increase in Europe will be greater than the global average. Added to this phenomenon is the fact that air quality improvement policies since the 1980s, which have significantly reduced pollution, have reduced the amount of aerosols. However, these aerosols have a cooling power, so their reduction has contributed to the recent temperature increase. Thus, the temperature increase in France over the last decade has reached 1.5 °C since the pre-industrial era (1860) compared to 1.1 °C on a global average. If we look in more detail at the spatial and seasonal distribution of future temperature increase, we see a greater increase in the north and centre of Europe than in the south during winter, while this increase will be stronger around the Mediterranean during summer. This greater increase in the North and Centre in winter is linked to the snow feedback whose coverage will significantly decrease with the rise in temperatures. Surfaces will thus be darker (decrease in albedo) and absorb more energy. The increase in temperatures in the South during summer is linked to a decrease in evapotranspiration and therefore its cooling effect (the soils being drier). Climate change, accompanied by an increase in climate variability, the increase in average temperatures combined with a higher probability of extreme hot events will lead to a significant increase in heatwave periods, which we have already been observing for several years (for example 2019, 2020, 2022 and 2023).

[6]The Clipssa project, built on a partnership involving in particular AFD, IRD, Météo-France, IAC, Criobe and the communities of the overseas territories and Vanuatu, is interested in these issues: www.clipssa.org.

Precipitation

Even though the uncertainty related to changes in precipitation is greater than for temperatures, there is a consensus on a contrasting response between southern and northern Europe. During the winter, a large part of Europe should see an increase in its precipitation, while it will decrease around the Mediterranean. During the summer, a larger part of Southern Europe and a majority of Central Europe should see a decrease in precipitation, while from Germany to Scandinavia, precipitation should increase.

Extreme Events

Regarding extreme events, even though we should observe an increase in periods of summer droughts across a large part of Europe (except the extreme south and north) due to the combined effect of decreases in summer precipitation and higher temperatures, conversely, an increase in intense rainfall events is projected (Fig. 4.13). This phenomenon is explained by the increase in oceanic and atmospheric temperatures, which will lead to an increase in evaporation, and the increase in the capacity of the atmosphere to hold a larger amount of vapour. The amount of precipitable water will then be greater for given weather conditions. The indirect consequence will then be an increase in the frequency of floods.

Winds

There is no clear trend emerging in terms of the risk of storms. Even though their frequency should not increase, it is possible that an increase in their intensity may occur, particularly due to the accentuation of thermal contrasts between the ocean and the continents. This remains hypothetical and it is therefore difficult to conclude on the evolution of storm risk.

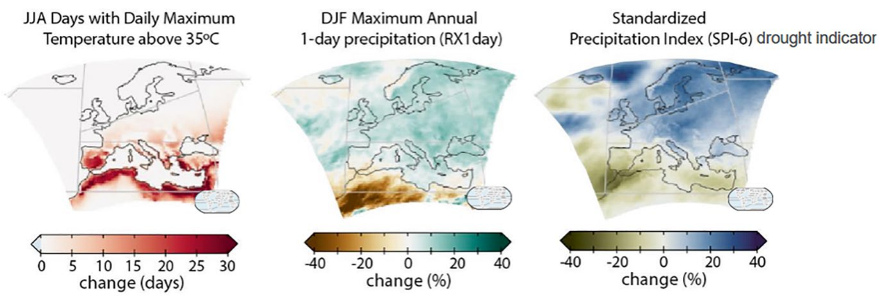


Fig. 4.13 Change in heatwave, heavy rain and drought indicators by 2050 for Europe. (Source: IPCC AR6 (2022))

Sea Level

The increase in temperatures has an impact on the rise in sea levels due to the melting of polar ice caps and the expansion of the oceans in connection with the increase in temperature (the proportion of these two factors being, at present, roughly equivalent). This concerns all European coastal areas. Due to the great inertia of the ocean, the rise in water levels will continue, even if we manage to stabilise atmospheric CO_2, long time after CO_2 begins to decrease. The sea level has risen by about 23 cm since 1880 and should gain another 30 cm by 2050 (IPCC 2013). The effect will be especially noticeable during episodes of storms combined with high tides which will increase the probabilities of submersion. It will also contribute to accentuating coastal erosion.

4.5.5.2 The Consequences of Climate Change on the Different Sectors of Agriculture in Europe

The effect of climate change will be contrasting, particularly between the south and the north of Europe. The combination of increasing temperatures and decreasing summer precipitation, particularly in southern Europe, will lead to an increase in periods of agricultural drought, especially noticeable around the Mediterranean. This will result in an increase in water stress and also thermal stress during the summer period, which will affect all agricultural sectors. Conversely, the increase in temperatures will allow for an earlier start to the vegetative cycle and an extension of this cycle. The impact will therefore be contrasting, both according to the type of crop and the regions (Fig. 4.14). With current agricultural practices, winter crops like wheat—which is relatively insensitive to summer drought, but can benefit from an earlier start—should see their yield increase in northern Europe, while they should slightly decrease in the Centre and the South. Similarly, soy, except in the most pessimistic scenario, should be able to be grown over a large part of Europe, where it is currently limited to a latitude of 50° N. Only Spain would see its yields decrease. However, maize, which is very water-demanding and grows during the summer, could only maintain its yields over a large part of Europe at the cost of a significant increase in irrigation which seems difficult to achieve and would lead to a strong usage tension on the water resource, already noticeable today. In terms of adaptation, new crops, like sorghum for animal feed, requiring less water and well adapted to high temperatures, could be developed particularly in the south and the centre of Europe. The increase in periods of heatwaves and droughts will also strongly affect the forestry sector, where an increase in diebacks is already being observed, particularly for species like Douglas fir or beech, which are very sensitive to water stress. Droughts and heatwaves also significantly increase the risk of fire which will then become possible over a large part of Europe. In 2022, a significant fire occurred in the Armorican forest, which had never happened before. For the livestock sector, droughts will decrease summer forage production. This

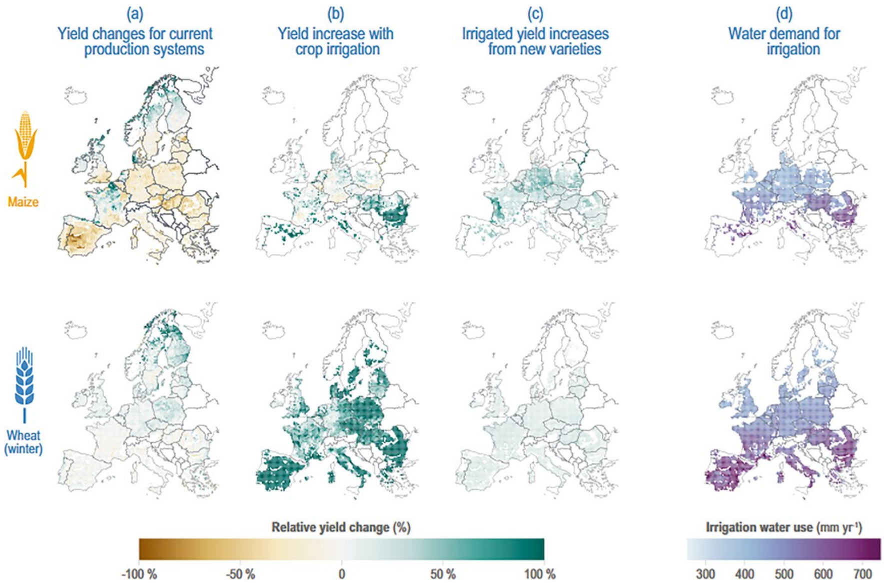


Fig. 4.14 Changes in wheat and maize yields in Europe for current practices and considering adaptations with associated water demands for a 2 °C temperature increase scenario. (Source: Bednar-Friedl et al. (2022))

phenomenon could however be partly compensated by earlier growth in spring and the possibility of grazing herds earlier and making summer forage stocks, which were usually intended for the winter period which on the contrary will shorten. But the increase in heatwaves will also pose a direct problem for livestock. The enteric fermentation of ruminants being exothermic, they are very sensitive to high temperatures, forcing them to reduce grazing in high heat, This reduces the production of meat or milk accordingly.

Another phenomenon linked to the increase in temperatures is paradoxically the increased risk of frost at the beginning of the vegetative cycle. Indeed, although the dates of the last frosts are becoming earlier and earlier, the advancement of the vegetative cycle linked to the increase in winter temperatures is faster than that of the period of the last frosts, thus increasing the risk that a frost occurs during the critical phases of bud burst and flowering. Vineyards and early fruit trees are particularly vulnerable in this regard.

4.5.5.3 Contribution of the Agricultural Sector to the Greenhouse Gas Balance

It is estimated that agriculture is responsible for 11.4% of greenhouse gas emissions at the European level, out of a total of 3.31 billion t eqCO_2. The share of greenhouse gas emissions from agricultural sources varies from one member state to another.

France is the country that emits the most in this sector, with 85 Mt of CO_2, followed by Germany (66 Mt) and Poland (57 Mt). These emissions are linked to various factors. There are of course CO_2 emissions related to fuel consumption across the farm and for the manufacture of inputs and phytosanitary products, but a large part of the emissions are also linked to methane (CH_4) produced by ruminants and nitrous oxide (N_2O) linked to fertilisers. The emissions of CH_4 are estimated at 5 Mt and those of N_2O at 660 Mt. As mentioned in the introduction, although these emissions are low, the global warming potential of CH_4 and N_2O is much greater than that of CO_2. But the lifespan of these different molecules also needs to be taken into account. Agricultural practices also affect the CO_2 balance by altering soil carbon. For example, in France (the situation is similar in the rest of Europe), areas of large-scale farming have already lost a large part of their soil carbon and continue to be a very slight source of carbon at 0.06 t eqCO_2/ha/year. But agriculture can also contribute to the sequestration of carbon in soils and thus to the mitigation of climate change. In France, grassland and forest soils have significant soil carbon contents (respectively 84 t/ha and 81 t/ha) and represent a carbon sink (from 0.37 to 0.80 t eqCO_2/ha/year for grasslands, and from 1.60 to 5.06 t eqCO_2/ha/year for forests depending on the studies) (EFESE Report 2019; INRAE Report 2020). Therefore, it is especially important to maintain existing stocks in grasslands and forests. Thus, reforestation, particularly linked to the abandonment of old agricultural lands over the last few decades (+ 9% in thirty years), has contributed to making the continent a carbon sink (excluding anthropogenic emissions). In general, large-scale crops, due to their low amount of carbon in the soil, offer significant storage potential. The most promising avenues are agroecology, the use of intermediate crops and the reconstitution of hedges (INRAE Report 2020). Even though concrete achievements are still very underdeveloped (compared to the United States for example), the European approach is much more systemic. Indeed, nature-based solutions must follow the recommendations of the IUCN by taking into account the impact of the proposed solutions on all ecosystem services.

4.5.6 The Anticipated Climate Changes and Impacts in North America

Nicolas Viovy

4.5.6.1 The Climate Changes in North America

Temperature

The increase in temperature will affect the entire North American continent (Lee et al. 2021) (Fig. 4.15). This temperature increase in North America will be greater than the global average. Upon closer examination of the spatial and seasonal

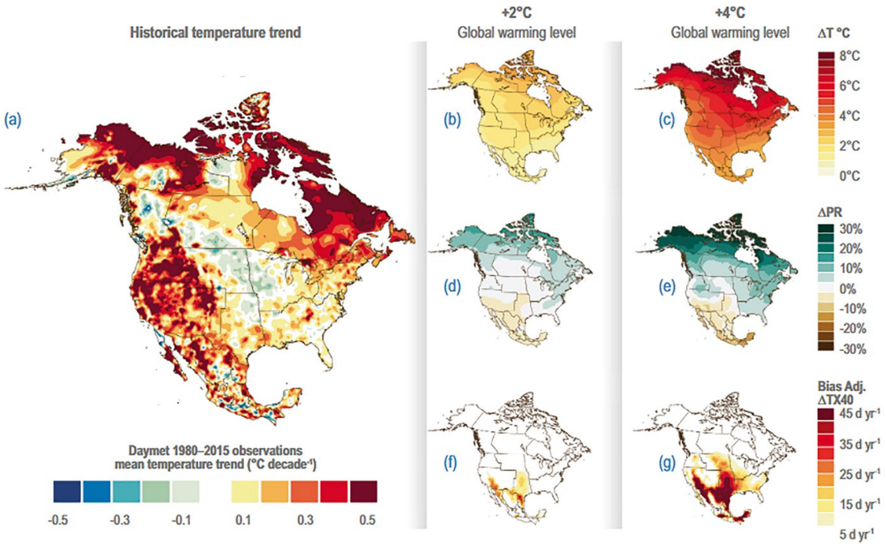


Fig. 4.15 Observed and projected climate change for North America. (Source: Hicke et al. (2022)) (**a**) Observed temperature trend from 1980 to 2015; (**b** and **c**) temperature change for scenarios +2 °C and +4 °C (ΔT); (**d** and **e**) change in precipitation (ΔPR); (**f** and **g**) change in the number of days with a temperature above 40 °C (ΔTX40) (Hsiang et al. 2017)

distribution of future temperature increase, an increase that grows with latitude and will also be more significant in the centre of the continent than on the coastal areas is observed. This stronger increase in the North and Centre in winter is linked to the snow feedback, whose coverage will significantly decrease with the rise in temperatures. The surfaces will thus be darker and absorb more energy. This also explains why the temperature increase will be particularly strong in winter in the northern part of the continent. In the scenario of a global average increase of 4 °C compared to the pre-industrial era, the increase in summer temperatures would also become very significant. Climate change, accompanied by an increase in climate variability, the increase in average temperatures combined with a higher probability of extreme hot events will lead to a significant increase in heatwave periods. This increase in temperatures and heatwaves will result in an increased risk of fire, particularly in the boreal zone. The 2023 fires in Canada, for example, destroyed 17 Mha. In the United States, the central west part should experience the greatest increases, both in the south (such as Arizona or Texas) and further north (in Montana and Dakota). Furthermore, the increase in the number of days where the temperature exceeds 40 °C in Texas or Arizona compared to the historical period could reach about thirty days per year (Lee et al. 2021). The average temperature increase being stronger in high latitudes than in the tropics, the latter will be even more pronounced in Canada than in the United States. In particular, a significant decrease in the freezing of soils, lakes and rivers can be expected, with consequences on soil stability (linked to the melting of permafrost) or on the modification of transport systems (the installation of camps or temporary roads on frozen lakes becoming impossible).

Precipitation

Even though the uncertainty related to precipitation change is greater than for temperatures, the emerging trends are an increase in winter precipitation, strong in the North, moderate in the Centre, but a significant decrease in precipitation over California, Arizona and New Mexico. During the summer, precipitation should increase in the North, but on the contrary decrease in the Centre. In Canada, precipitation should increase on average, particularly in the North.

Extreme Events

Regarding extreme events, an increase in periods of summer droughts should be observed, particularly across the entire central part to the west of the United States in line with heatwave areas, linked to the combined effect of decreases in summer precipitation and higher temperatures. Conversely, the IPCC modellers project an increase in intense rainfall events (Lee et al. 2021), which should be particularly marked in the north-west and north-east of the continent with the indirect consequence of an increase in flood frequencies. This phenomenon is explained both by the increase in oceanic and atmospheric temperatures, which will lead to an increase in evaporation, and by the increase in the atmosphere's capacity to hold a larger amount of vapour. The amount of precipitable water will then be greater for given weather conditions.

Winds

The United States is subject to frequent tornadoes. While it is difficult to estimate whether their number or intensity are likely to increase, it is very clear that there is a shift of the "tornado alley" towards the east of the continent, which should intensify in the future. This can be linked to the drying out of the central west mentioned above. Similarly, the southeast of the United States, particularly Florida, can be affected by hurricanes. However, while there is no emerging trend on a change in hurricane frequency, an increase in their intensity is projected. Similarly, the increase in ocean temperatures should lead to a further northward shift of cyclones, which could also affect the north of the east coast.

4.5.6.2 The Consequences of Climate Change on the Various Sectors of Agriculture in North America

The effect of climate change will be contrasted between the east and the west of the continent. In the East, climate change should lead to a notable decrease in yield and more generally in the South, while in the West some areas could see their yield increase (Fig. 4.16). However, it should be noted that it is precisely the large

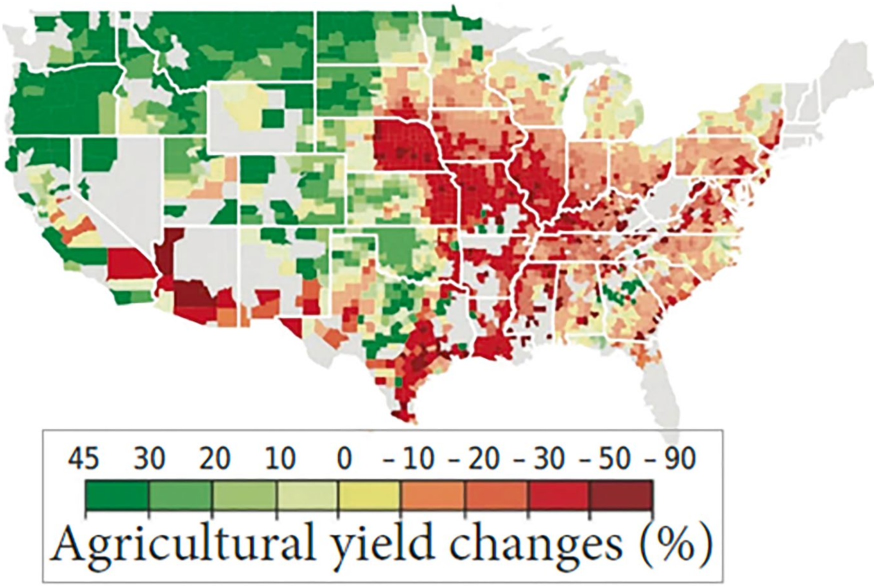


Fig. 4.16 Projected evolution of agricultural yield (all crops combined) between 2080 and 2099, under an RCP8 scenario. (Source: Hsiang et al. (2017))

agricultural plains of the Midwest, including the Corn Belt, which are expected to be heavily affected, while the areas where the yields could increase are not currently significant crop areas. This global view actually masks a wide disparity depending on the type of crop. Corn, particularly sensitive to summer drought due to high water demand and development in mid-summer, will be the most affected. Soybeans, which are also a summer crop, will also be negatively impacted although a little less than corn. On the other hand, wheat, which matures before the periods of drought, should benefit from an earlier emergence and thus see its yield increase. The maintenance of corn cultivation would require a significant increase in irrigation, but at the cost of an increase in available water volumes which would further accentuate the strong tensions on the already very constrained water resource. Climate change will also severely affect the forestry sector across the entire North American continent, both through increased fire risks and also through changes in species distribution ranges. In the centre, the increase in periods of heatwaves and droughts will heavily affect the forestry sector, where an increase in dieback is already being observed. Only the northern coastal areas, which are not limited in water and benefit from an extension of the growing period, should on the contrary benefit from climate change. For the livestock sector, droughts will decrease summer forage production. As in Europe, this phenomenon could however be partly compensated by earlier growth in spring and the possibility of grazing the herds earlier. But the increase in heatwaves will also pose a direct problem for livestock. The enteric fermentation of ruminants being exothermic, they are very sensitive to high temperatures, forcing them to reduce grazing in high heat, thereby reducing meat or milk production.

Another phenomenon related to the increase in temperatures is, paradoxically, the increase in the risk of frost in the early vegetative cycle. Indeed, although the dates of the last frosts are becoming earlier and earlier, the advancement of the vegetative cycle linked to the increase in winter temperatures is faster than that of the period of the last frosts, thereby increasing the risk of a frost occurring during the critical phases of budburst and flowering. Consequently, as on the European continent, early vine and fruit trees are the most vulnerable in this regard.

4.5.6.3 Contribution of the Agricultural Sector to the Greenhouse Gas Balance

The United States Department of Agriculture (USDA) estimates that agriculture is responsible for 11% of greenhouse gas emissions in the United States and 8% in Canada, out of a total of approximately 6.6 billion tonnes of CO_2 equivalent. This percentage of emissions linked to agriculture is close to the European fig (9%). Emissions per kilogram produced are, for example, around 30 kg CO_2 eq/kg for cattle (in carcass weight and not live weight) compared to 0.2 kg for cereals on average across the continent (FAOSTAT 2022 data[7]). Greenhouse gas emissions from the agricultural sector per capita are much higher in North America than in Europe (1.2 t CO_2 eq in the United States, 1.5 t CO_2 eq in Canada, compared to 0.87 t CO_2 eq in Europe) (Climate watch 2024 data[8]). This is due to both the ratio between plant and animal production (animal production being much more emitting), but also to the quantity produced per capita, which is higher in North America (around 2.9 t/inhab. Compared to about 2.3 t/inhab. in Europe). These emissions are linked to various factors. There are of course CO_2 emissions related to machinery, the manufacture of inputs and phytosanitary products, but a large part of the emissions are also linked to methane (CH_4) emissions produced by ruminants and rice fields, and nitrous oxide (N_2O), for the manufacture and use of chemical fertilisers. Annual emissions for the United States are estimated at 20 Mt for CH_4 and 930 Mt for N_2O. Although these emissions are low, the global warming potential of CH_4 and N_2O is much higher than that of CO_2 (28 times for CH_4, 273 times for N_2O), their effect on the radiative balance is very significant. It is also important to keep in mind the lifespan of these different molecules in the air. CH_4 has a lifespan of about 10 years; this duration is not negligible, but less problematic than that of N_2O which is 120 years. Agricultural practices also affect the CO_2 balance by modifying soil carbon. Therefore, it is especially important to maintain existing stocks in grasslands and forests. Even if agricultural practices are not to blame, the mega-fires of recent years in the west of the continent have destroyed large areas of forests. For example, the

[7] https://openknowledge.fao.org/server/api/core/bitstreams/cc09fbbc-eb1d-436b-a88a-bed42a1f12f3/content

[8] https://www.climatewatchdata.org/.

mega-fires of 2023 in Canada emitted 431 Mt of carbon (compared to 59 Mt on average each year), and significant reforestation programmes are planned in the United States which should help to rebuild some of the stocks. Unmanaged reforestation (i.e., linked to the abandonment of old agricultural lands over the last few decades), even though it is much weaker than in Europe for example, has partially contributed to making the continent a carbon sink (excluding anthropogenic emissions).

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