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23 Global Change and Terrestrial Ecosystems

Effects of thousands of years of land use and soil erosion in a subarid climate. The Middle East is considered to be one of the oldest farming areas on Earth. Deforestation and agricultural use over centuries led to erosion of soil from slopes and to re-allocation of fine soil particles towards the valley floor. The photo shows an agricultural area near Hebron, currently under Israeli administration. From traces of foot paths it can be seen that slopes were grazed. Small fields on slopes are used for cereal crops. Fruit trees can only grow at the valley floor where stone walls prevent loss of topsoil during heavy rain events. Barley and wheat are the predominant cereals, almond, apricot, pomegranate, olives and peaches are the main fruit trees. (Photo E-D Schulze)

With increasing human population and their demands, there is an increasing need for land that can be cultivated or managed for resources to feed human needs. It is being expected that by 2050 also remote regions and areas of low productivity will be appropriated by humans for their own needs (Canadell and Schulze 2014).

23.1 Global Change

Global change is a widely accepted term. According to an early definition by the International Geosphere-Biosphere Program (IGBP), global change includes changes of atmospheric circulation, ocean circulation, climate, the carbon cycle, the nitrogen cycle, the water cycle and other cycles, sea-ice changes, sea-level changes, food webs, biological diversity, pollution, health, fish stocks, [...] population, the economy, resource use, energy, development, transport, communication, land use and land cover, urbanization, globalization” (http://www.igbp.net). Other definitions furthermore include global freshwater use, ocean acidification, stratospheric ozone depletion and atmospheric aerosol loading. Thus, global change encompasses all possible anthropogenic changes at the scale of the globe as a whole. In terms of plant ecology, global change refers mainly to changes in land use, climate, and biodiversity.

During geological times, changes in the Earth's climate and vegetation have always occurred independently of human activities, and human influences on Earth are not restricted to the present time (see also Chapter 17.2). Human appropriation of nature started at the transition...
from Pliocene to Pleistocene about two million years ago in the savannahs of East Africa. 1.8 million years ago (Lower Pleistocene), early humans (*Homo erectus*) spread in several migration waves across the planet (e.g. Balter and Gibbons 2000). *H. sapiens* evolved from *H. erectus* about 200,000 years ago (Middle Pleistocene) in Africa. At about the same time *H. neanderthalensis* evolved from *H. erectus* in Europe. The first evidence of *H. sapiens* in Europe dates to about 40,000 years ago (Cro-Magnon period). Intensive settlement in the Mediterranean region started about 30,000 years ago (before peak glaciation of the last glacial period), when *H. sapiens* lived together with *H. neanderthalensis* in southern Europe (Gibbons 2001). North America was reached by humans only about 19,000 years ago, while Australia was reached already 50,000 years ago (Harcourt 2016). However, since about 130 years the rate and the extent of climate and vegetation changes caused by human activity have increased such that the surface of the Earth has changed profoundly.

**Fig. 23.1 Human population.** A Global population density at 3000 BC and 2000 AD (after Klein Goldewijk 2010). B Estimated world rural and urban population growth between 1960 and 2050 (Chart1: FAO 2013)
The transition from hunting and gathering to agriculture and animal domestication occurred in East Africa and East Asia about 11,000 years ago. Since then, a steady but slow increase in human population took place along with increased land-use change (mainly by deforestation) for space of grazing animals and agriculture. The invention of agriculture resulted in an increase of the world population from an estimated 2 million 5,000 years ago to about 1 billion in 1800 (Klein Goldewijk 2010; Fig. 23.1). Since 1800, the global population increased by the factor of 7 to reach 7 billion in 2013 (Klein Goldewijk 2010). However, Ellis et al. (2013) point out that a relatively small human population likely caused profound and widespread ecological changes already 3,000 years ago. Recent advances in medicine, chemistry, technology and molecular biology caused an unprecedented population increase at the expense of the natural environment. Based on these changes, Crutzen (2002) proposed a new epoch in Earth history, the Anthropocene, starting with changes in the global atmospheric composition. Since defining geological times by stratification of specific geological layers is in the responsibility of the science of Geology, a discussion arose about which activity of humans could be identified as geological layer in millions of years ahead (Lewis and Maslin 2015). In fact, the geological Epoch of the “Holocene” was defined as the period of increased human activity already. Thus, it is not resolved of how to classify and separate the Holocene from the Anthropocene in geological terms. At present, the atomic bomb tests with a peak in radioactive isotopes by 1964, or the accumulation of plastic materials in oceans and flood plains after 1950 could serve as such geological evidence for the start of a new Geological Epoch.

Since human life is dependent on various ecosystem services (see Chapter 21.3), specific questions about the role of plant ecology for global change arise:

- What are the effects of changes in climate, land-use and biodiversity on terrestrial ecosystems?
- What are the feedbacks of changes in terrestrial ecosystems on ecosystem services?

It emerges (Fig. 23.2) that not the human population by itself, but the intensity of human activities as executed by a relative minority of the population results in changes of land use, global biogeochemistry, and of biotic assemblages which in turn result in climate change and in a loss of biological diversity. Both these changes will feed back on human activities as modulated by the socio-economic conditions (see Chapter 20, Fig. 20.1).
Fig. 23.2 Schematic illustration of the interaction between human activity and global change. Human population size and use of resources via specific activities (agriculture, industry, recreation and trade) have effects on land use, the global biogeochemical cycles and biodiversity. These influences initiate changes in climate and in biodiversity and both, in turn, influence populations and resources used by people. How this feedback occurs, and how strong it is, depends on socio-economic parameters. Thus, it is difficult to predict scientifically how climate change will affect the situation in developed and in developing countries (after Vitousek et al. 1997)

23.2 Land Use and Land-Use Change

The terminology of “land use”, LU, and “land-use change”, LUC, originated from the Kyoto Protocol (see Chapter 23.5) and the intention to financially account for afforestation, reforestation and deforestation (ARD) activities. The definitions of LULUC were the focus of a Special Report of the Intergovernmental Panel on Climate Change (IPCC) under the title “Land use, Land-Use Change, and Forestry” (Watson et al. 2000). In this report, “land use” was for the first time clearly defined as “a change affecting the amount of biomass in existing biomass stocks by management”, while “land-use change” is “a change in the way land is used” (e.g. change from forestry towards agriculture). Land cover is an additional term, which partly overlaps with LULUC, but also includes natural vegetation. It is “the physical
and biological cover of the Earth’s land as vegetation or man-made feature”; however, it
neglects the intensity of land use (see Chapter 21.1).

**Land use and land-use change (LULUC)** thus affect the vegetation by changing the
vegetation cover as well as soils by erosion, salinity, desertification, and eutrophication. This
in turn changes the biogeochemical cycles of carbon, nutrients and water, causing additional
emissions of greenhouse gases such as CO₂, N₂O and CH₄.

### 23.2.1 Changes in Land Use and Land-Use Change

According to the FAO, global agricultural production increased over the past decade by about
2% per year, although the cultivated area increased only by 1%. About 40% of our food
production comes from irrigated land, although this only accounts for 20% of the cultivated
land. The area of irrigated land had doubled over the same period of time. Irrigation has
therefore indirectly relieved the pressure on land expansion, and thus helped protecting
natural vegetation (see Chapter 23.5). However, the other side of the coin is a possible
accumulation of salt (NaCl) by irrigation, and an associated abandonment of land area due to
salinity and erosion (see Chapter 17.2). Further examples of salinisation following LUC come
from Australia where salt from deep soil layers was brought to the surface with the change in
rooting depth of agricultural plants compared to native *Eucalyptus* trees. Moreover, irrigation
is often based on groundwater in many parts of the world (e.g. fossil, Pleistocene water below
the Sahara) and not from renewable freshwater sources. These groundwater reservoirs are
limited and their recharge rates are slow and highly variable. They range from < 10 mm year⁻¹
in semi-arid rangeland to 580 mm year⁻¹ in irrigation-dominated agriculture, overall
accounting for about 22% of annual precipitation. Mean residence times are about 300 years
(see Chapter 21.2).

**Forestry** also has large impacts on land use, but agriculture determines land-use change.
Forests cover about 30% of the global ice-free land area (about 40 million km²), with about
7% of these forests being planted, and 93% being natural or semi-natural with natural
regeneration (FAO 2015). Presently, the increased requirements for animal feed, timber for
construction, and palm oil still result in large scale LUC, mainly in the tropics. Hot spots of
tropical LUC are Brazil and Indonesia, with deforestation rates up to 40,000 km² yr⁻¹. The
global forest loss has recently been quantified for the period from 2000-2012 using Earth
repeated observation data at a spatial resolution of 30 m. Hansen et al. (2013) estimated global forest loss at about 2.3 million km² over 12 years, mainly in tropical and boreal zones. During the same time, afforestation occurred over only 0.8 million km², mainly in subtropical and temperate regions (Fig. 23.3). In comparison, the FAO (2015) reported net forest cover loss between 1990 and 2015 of 14.7 million km² (4 million km² between 2000 and 2010), which is larger than the estimate by Hansen et al. (2013) for approximately the same time period. This indicates the large uncertainties of any of these global estimates in forest gains and losses.

**Fig. 23.3 Changes in tree cover and global forest loss and gain during the 21st century.**

Areas with forest loss are mainly used for agriculture. Map is based on remotely sensed data during 2000 and 2012, at a spatial resolution of 30 m. (from Hansen et al. 2013). Green shows areas with increased tree cover, red shows areas with increasing forest loss, and blue shows areas with increasing forest gain. The magenta areas summarise losses and gains. The grey areas are regions without any change in forest areas.

In surveying these changes from satellites it should be emphasised that land cover and related LUC can only be detected by repeated satellite observations because otherwise harvesting of forest would be recorded as deforestation under the category of LUC, even though it might be part of sustainable forest management that is followed by forest regeneration (see Chapter 14.1). In contrast, clearings around infrastructures and the breakdown of fragmented forest remnants would add to observed deforestations, but this is generally not recorded (Laurance et al. 1997). Forest degradation due to fire and damages by selective logging of native forests are not included either (Nepstad et al. 1999). Thus, there remains a large uncertainty for forest cover maps.
Deforestation and afforestation are asymmetric in their effects on **global climate**. Prentice et al. (2001) showed that afforesting all areas that had been cleared by humankind since the Industrial Revolution would decrease the atmospheric CO$_2$ concentration by only 40 ppm, whilst clearing the existing primary forests would lead to an increase by about 200–400 ppm. Thus, CO$_2$ emissions by LUC clearly increased anthropogenic CO$_2$ emissions. However, compared to emissions from **fossil fuel burning** (9.3 ± 0.5 Gt C yr$^{-1}$ in 2006 until 2015), emissions from land-use change are relatively small, but increasing (1.0 ± 0.5 Gt C yr$^{-1}$; Le Quéré et al. 2016).

It should be noted that the human appropriation of land by LUC mainly serves the demands of the industrialised world. Fig. 23.4A shows the main agricultural cropping regions and **agricultural grain yields** of 175 crop types of the world. Additional land is needed for **bioenergy** (Fig. 23.4 B and C), which shows a large trade flux of ethanol and biodiesel from South America and USA to Europe (SRREN 2011).
Fig. 23.4 Global maps of agricultural production and of trade for wood pellets and biofuels. A Global map of agricultural production for 175 crop types (West et al. 2010). B Global trade of wood pellets in 2009. Size of arrows increase with larger trade volume given in PJ. C Global biofuel production and trade. Histograms and flows in orange represent ethanol, in blue biodiesel (from SRREN 2011).

The crop types with the largest grain yield globally are maize, rice and wheat (Tab. 23.1). As maize, soybeans are produced for both human and animal use. Potatoes, sorghum and barley are produced much less. Global sugar production is mainly by sugar cane, but with large continental differences: while in the Americas sugar originates mainly from sugar cane (C₄ plant), in Europe sugar beet (C₃ plant) dominates. Additional large areas are needed for cattle grazing (see Chapter 21.1). Nevertheless, meat production is as variable across the globe as crop production (Tab. 23.1). While pigs are mainly produced in Asia, chicken dominate in the Americas and Asia, while cattle clearly dominates in the Americas. As with pellets and biofuels, all these commodities are traded globally. Excellent statistics can be found at the FAO webpage.

Tab. 23.1 Production of crops and meat from primary livestock across global regions.
Production is given in % of global production for each region, averaged over the years 2010 to 2014. Maximum production is given in mio t per country, also averaged over 2010 to 2014. Top five producers are given. Maize production does not include green maize production.

<table>
<thead>
<tr>
<th>Production</th>
<th>Maize</th>
<th>Rice</th>
<th>Wheat</th>
<th>Soybeans</th>
<th>Potatoes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Zea mays</em></td>
<td>(paddy)</td>
<td></td>
<td><em>Glycine max</em></td>
<td></td>
</tr>
<tr>
<td>Region</td>
<td><em>Oryza sativa</em></td>
<td><em>Triticum aesticum</em></td>
<td><em>Solanum tuberosum</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Americas</td>
<td>50.4</td>
<td>5.0</td>
<td>16.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>7.5</td>
<td>3.9</td>
<td>3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>30.5</td>
<td>90.4</td>
<td>44.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>11.6</td>
<td>0.6</td>
<td>31.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>0.1</td>
<td>0.1</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Max. production</strong></td>
<td>323.2</td>
<td>202.2</td>
<td>120.3</td>
<td>91.2</td>
<td>90.8</td>
</tr>
<tr>
<td><strong>Top 5 producers</strong></td>
<td>USA, China, Brazil, Argentina, Ukraine</td>
<td>China, India, Russia, Bangladesh, Viet Nam</td>
<td>China, India, Russia, France, Ukraine, USA</td>
<td>USA, Brazil, Argentina, Russia, China, India</td>
<td>USA, Brazil, Argentina, Russia, China, India</td>
</tr>
<tr>
<td>Production</td>
<td><em>Sorghum bicolor</em></td>
<td><em>Hordeum vulgare</em></td>
<td><em>Saccharum officinale</em></td>
<td><em>Beta vulgaris</em></td>
<td><em>Musa paradisica</em></td>
</tr>
<tr>
<td>Americas</td>
<td>37.5</td>
<td>13.2</td>
<td>54.1</td>
<td>12.2</td>
<td>25.2</td>
</tr>
<tr>
<td>Africa</td>
<td>41.5</td>
<td>4.7</td>
<td>5.1</td>
<td>4.5</td>
<td>17.9</td>
</tr>
<tr>
<td>Asia</td>
<td>16.3</td>
<td>14.7</td>
<td>39.1</td>
<td>13.7</td>
<td>55.1</td>
</tr>
<tr>
<td>Europe</td>
<td>1.6</td>
<td>61.1</td>
<td>0</td>
<td>69.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Oceania</td>
<td>3.1</td>
<td>6.2</td>
<td>1.7</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Max. production</strong></td>
<td>83.0</td>
<td>15.0</td>
<td>735.4</td>
<td>37.6</td>
<td>28.4</td>
</tr>
<tr>
<td><strong>Top 5 producers</strong></td>
<td>USA, Mexico, Nigeria, India, Sudan</td>
<td>Russia, India, France, Germany, Ukraine, Canada</td>
<td>Brazil, Russia, China, Thailand, Pakistan</td>
<td>India, China, Philippines, Ecuador, Brazil</td>
<td>USA, Brazil, Argentina, Russia, China, India</td>
</tr>
<tr>
<td><strong>Primary livestock</strong></td>
<td>Pigs</td>
<td>Chicken</td>
<td>Cattle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Americas</td>
<td>17.3</td>
<td>45.9</td>
<td>48.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>1.1</td>
<td>4.9</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>56.5</td>
<td>32.4</td>
<td>21.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>24.6</td>
<td>16.4</td>
<td>16.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The effects of land use on the water, nutrient and carbon fluxes in ecosystems are highly relevant. The impacts of land use start with forest grazing and collection of firewood, and continue to intensive management (Tab. 23.2). Changes in resource availability for plants and microorganisms in managed (agriculture and forestry) and unmanaged systems (incl. conservation areas) are either by direct supply of resources (fertilisation, irrigation) or indirect via atmospheric deposition and runoff, or by expanding large herbivores populations, such as deer, after the extinction of predators. Many land use practices clearly affect soil structure and climate (e.g. soil temperature, soil moisture), but also competition among plants (increased resource supply, opening of stand structure with fire and grazing, leading to selection of tolerant species). For example, the effects of browsing by wild ungulates in temperate forests resulted in the selection of browsing tolerant species such as *Fagus* in Europe (Schulze et al. 2014). Structural responses were found in natural subtropical woodlands (Asner et al. 2009). Positive (increased growth, regeneration) as well as negative consequences (change in biodiversity, invasion, erosion) can follow. At the same time, all land use practices also trigger feedbacks of the ecosystems under use on the atmosphere and thus climate (trace gas fluxes, changes in albedo and in evapotranspiration). Moreover, adjacent ecosystems can be impacted as well (runoff, erosion). Impacts on biodiversity will be discussed in more detail later (see Chapter 23.4).

Tab. 23.2 Factors contributing to agricultural and forest land use as well as consequences for terrestrial ecosystems and their feedbacks on the environment. The table will never be complete in terms of consequences and feedbacks on the environment, i.e.

<table>
<thead>
<tr>
<th>Oceania</th>
<th>0.4</th>
<th>1.3</th>
<th>4.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. production</td>
<td>51.1</td>
<td>17.2</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Top 5 producers
- China, USA, Germany, Spain, Brazil
- USA, China, Brazil, Russian Federation, Mexico
- USA, China, Brazil, Argentina, Mexico
adjacent ecosystems, the atmosphere and the hydrosphere, because impacts of land use vary with frequency and intensity of land use.

<table>
<thead>
<tr>
<th>Factors contributing to LU</th>
<th>Consequences for ecosystem</th>
<th>Feedbacks on environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land conversion</td>
<td>Loss of soil C and nutrient pools, erosion, loss of biodiversity</td>
<td>Change in water fluxes and evaporative cooling, and in albedo, input of nutrients</td>
</tr>
<tr>
<td>Fire</td>
<td>Loss of C and nutrients, deposition of soot, changes in soil climate, increased microbial mineralisation, runoff, erosion, weed control, loss of vegetation, opportunity for regeneration</td>
<td>Change in albedo, change in water and nutrient fluxes, input of nutrients via runoff</td>
</tr>
<tr>
<td>Soil management</td>
<td>Change in soil structure and water holding capacity, impacts on soil biota, change in weed pressure, danger of erosion</td>
<td>Change in nutrient inputs via runoff, trace gas fluxes</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Increased water availability, salinisation, change in inter-specific competition, increased growth</td>
<td>Increase in evapotranspiration and evaporative cooling, decrease in groundwater depth</td>
</tr>
<tr>
<td>Fertilisation</td>
<td>Increased nutrient availability, change in inter-specific competition, increased growth</td>
<td>Leaching of nutrients, eutrophication, trace gas fluxes</td>
</tr>
<tr>
<td>Pesticide application</td>
<td>Change in inter-specific competition, weed and pest control, increased growth</td>
<td>Lateral spread of pesticides</td>
</tr>
<tr>
<td>Harvest</td>
<td>Loss of vegetation, change in soil climate, impacts on soil biota, danger of erosion</td>
<td>Change in water fluxes and evaporative cooling, change in albedo, trace gas fluxes</td>
</tr>
<tr>
<td>Grazing/browsing</td>
<td>Partial loss of vegetation, change in competition, impacts on soil biota, change in soil structure, danger of erosion</td>
<td>Change in water fluxes and evaporative cooling, change in albedo, trace gas fluxes, input of nutrients via runoff</td>
</tr>
<tr>
<td>Introduction of alien species</td>
<td>Change in competition, loss of biodiversity, impacts on soil biota, change in fire frequency</td>
<td>Change in nutrient and water fluxes, erosion</td>
</tr>
</tbody>
</table>

Over time, land use has changed even for the same ecosystem type (e.g. tropical forest or semi-arid rangeland) or land cover (e.g. forest or grassland), due to changes in human needs (gathering of fruits vs. timber harvests in tropical forests) or land use practise (deep ploughing vs. no till). Moreover, there are management practices that are capable to restore degraded systems, e.g. no or low tillage, conservation tillage, mulching, organic residue management. The effects of LUC on the C budget were analysed for the USA because historical changes of land acquisition by European immigrants could still be reconstructed (Fig. 23.5; Houghton et
al. 1999). About $27 \times 10^9$ t C were released by changing prairie grasslands into agricultural cropland and by use of wood for energy and construction between 1770 and 1945. Maximum emissions occurred around 1880, but these emissions decreased after 1900, because there was no more land to be changed. Since 1945, the trend reversed due to fighting fires and to forest succession on abandoned land. Soils started to accumulate C again since about 1970 due to furrow cultivation (Matson et al. 1970). Thus, LULUC are very dynamic processes that can be managed in positive and negative ways (see Tab. 23.2). This knowledge of land management is often the basis for international agreements, such as the Kyoto or the Paris Protocols (see Chapter 23.5), for future handling of the Earth in a sustainable manner.

Fig. 23.5 Historic changes in C fluxes following land-use change in the USA. Annual CO₂ fluxes (C source depicted as positive value and C sink as negative value) of the USA from agricultural land, forests and fires. Emissions increased after 1750 due to deforestation, reaching a maximum around 1900. Subsequently, emission fluxes decreased and the land became C sink (negative values) around 1950. Recently, this C sink has decreased again, in part due to changes in land use intensity. (Houghton et al. 1999)

LULUC is not only restricted to agriculture and forestry, but also includes urban settlements and establishing infrastructure for human activities, such as highways, reservoirs or dams. The water cycle is strongly affected by reservoirs and dams (see Chapters 16, 21). This can result in regional desertification, i.e. degradation of land as defined by the UN Convention to Combat Desertification (see Chapters 17.2, 23.5). Examples include the reduced flow of the
Colorado river in Arizona as well as the drying out of the Aral Sea in Russia and of Lake Chad in the Sahel (Fig. 23.6).

**Fig. 23.6 Drying of Lake Chad between 1972 to 2001.** (From UNEP 2006)

LUC does not only influence the water balance, but also **water quality**. **Eutrophication** from households and industry, inputs of organic materials, heavy metals, high salt loads as well as N deposition and – as the newcomer – nanoparticles and plastic waste contribute to water pollution. In particular, large N and phosphorus (P) fertiliser inputs to agricultural lands are still problematic. Globally, N fertiliser use by plants is still below 50%. Nitrate leaching, NH$_3$ volatilisation as well as N$_2$O emissions are thus large N fluxes to the environment from many agricultural areas (see Tab. 23.2). About 1 to 7% of added N fertilisers are emitted as N$_2$O globally (Smith et al. 2016), making agricultural soils currently the major global source for N$_2$O (Reay et al. 2012). In contrast, agricultural sources of CH$_4$ originate from ruminants, rice cultivation, organic waste deposits, and biomass burning (Kirschke et al. 2013).

In Germany, the nitrate content in groundwater correlated linearly with **nitrogen deposition** from the atmosphere and fertilisation in agriculture (Lehn et al. 1996). In south-western Germany, a total of 550 water sources (more than 20% of the total number) were taken out of the water supply networks between 1980 and 1992 because of anthropogenic pollution, making long-distance water supplies and mixing water from different sources necessary.

Management of water pollution can be very complex as shown by the reduction of P contamination in **lakes** (Finlay et al. 2013). A decrease of P deposition into lakes will increase water quality in terms of oxygen concentrations in the water column, by avoiding algae blooms and associated eutrophication. However, the reduction of P inputs also affects other
biogeochemical cycles, for example the N cycle in lakes. Decreasing the number of algae blooms also limits their ‘benefits’. Algae incorporate (and thus remove) not only P and C from the water column, but also reactive N. When algae die, their dead tissues sink to the lake sediments. Here, they fuel denitrification by anaerobic microbes (Bernhardt et al. 2013), and nitrate is metabolised to N₂ and N₂O. However, in absence of P, the process that converts reactive N into inert atmospheric N₂ is missing, since no algae blooms are initiated. The now algae-free, but nitrogen-polluted fresh water lakes are stronger sources of N₂O than P-polluted waters (McCrackin and Elser 2010). This example shows that the management of biogeochemical cycles can contain many surprises due to the multiple interactions and feedbacks between organisms and biogeochemical processes.

23.3 Climate Change

23.3.1 Changes in Atmospheric Conditions

Climate change is strongly linked to the global carbon cycle since atmospheric CO₂ is one of the most important greenhouse gases responsible for global warming. Trace gases or greenhouse gases in the atmosphere reflect long-wave radiation back to the Earth’s surface which would normally reach the cosmos (back-radiation; see Chapter 9). The resulting temperature change is called global warming. Climate change scepticism is often based on the argument that climate has always been changing during Earth’s history as has the concentration of greenhouse gases. Indeed, ice core records did show that atmospheric CO₂ concentrations have been fluctuating between 172 and 300 ppm over the last 800,000 years (Lüthi et al. 2008). The CO₂ fluctuations caused by geological events were slow, and associated with glacial and interglacial cycles of millennia, caused by changes in the tilt of the Earth and the planetary circulation of the Earth around the Sun. The time scale during which past changes occurred is quite different from the time scale of present changes in the atmosphere, even though there had been fast events also in the past, such as the drainage of Lake Agassiz into the North Atlantic. Within the last 135 years, atmospheric CO₂ concentrations increased 120 ppm from 280 (so called pre-industrial) to 400 ppm (2016). This is equivalent to the magnitude of change that occurred during one glacial-interglacial cycle over about 100,000 years. The CO₂ concentration in the atmosphere has been increasing over the last decade on average by about 2.1 ppm per year (see Chapter 21; www.esrl.noaa.gov/).
The rise in CO₂ concentration has been measured continuously at Mauna Loa on Hawai`i since 1958, with minima corresponding to the growing season in the Northern Hemisphere summer and maxima corresponding to the dormant phase in winter when anthropogenic CO₂ production is also very high (Fig. 23.7A). A decrease in the oxygen concentration was observed in parallel to this increase in CO₂ at La Jolla, USA (Fig. 23.7A; Heimann 1997).

With increasing CO₂ concentrations also the δ¹³C in this CO₂ (atmospheric ¹³C/¹²C ratio compared with a standard) has been decreasing due to burning of fossil fuels which are highly depleted in ¹³C (negative δ¹³C; Fig. 23.7B). In pre-industrial times, the δ¹³C value (i.e. the atmospheric ¹³C/¹²C ratio compared to a standard) was –6.5‰. Adding CO₂ from fossil fuel sources has decreased the δ¹³C of atmospheric CO₂ by ca. 1.8‰ in the last 130 years, i.e. to about –8.3‰ in 2012. Plotting O₂ versus CO₂ concentration gives further evidence that the rise in CO₂ is caused by fossil fuel combustion and that it is not the consequence of natural CO₂ release, for example from volcanic activity or emissions by the oceans (Fig. 23.7C). When fossil fuels are burned, O₂ consumption is proportional to CO₂ release. However, since O₂ is also exchanged by the oceans (without releasing an equivalent amount of CO₂) and by photosynthesis (where CO₂ is simultaneously produced), measured CO₂ concentrations are lower than those postulated by fossil fuel burning alone (Keeling et al. 1996). This clearly indicates a global C sink. Thus, it has become clear from oxygen and stable carbon isotope measurements that the increased CO₂ concentrations in the atmosphere are a consequence of fossil fuel combustion.
Fig. 23.7 Time series of CO\textsubscript{2} concentrations, $\delta^{13}$C and O\textsubscript{2} concentrations as well as an analysis of the contribution of fossil fuel burning to atmospheric CO\textsubscript{2} concentrations. A CO\textsubscript{2} concentrations in the atmosphere are measured at Mauna Loa on Hawai`i since 1958. The simultaneous reduction in O\textsubscript{2} concentrations measured at La Jolla, California, is also shown. The O\textsubscript{2} concentrations show annual oscillations that are opposite to CO\textsubscript{2} (after Heimann 1997). B Changes in atmospheric CO\textsubscript{2} concentration and the $\delta^{13}$C value since 1700. C Changes in O\textsubscript{2} concentrations and relationship to CO\textsubscript{2} concentrations. (After Keeling et al. 1996)

For the decade 2006-2015, total anthropogenic CO\textsubscript{2} emissions were 10.3 Gt C yr\textsuperscript{-1} (1.0 ± 0.5 Gt C yr\textsuperscript{-1} from LUC plus 9.3 ± 0.5 Gt C yr\textsuperscript{-1} from fossil fuels), but during 2015 alone, they increased to 11.2 Gt C yr\textsuperscript{-1} (1.3 ± 0.5 Gt C yr\textsuperscript{-1} from LUC plus 9.9 ± 0.5 Gt C yr\textsuperscript{-1} from fossil fuels; Fig. 23.8A). The anthropogenic CO\textsubscript{2} emissions during 2006-2015 were partially balanced by uptake into the ocean (2.6 ± 0.5 Gt C yr\textsuperscript{-1}) and the land (3.1 ± 0.9 Gt C yr\textsuperscript{-1}, calculated as residual). However, for 2015 alone, the estimated terrestrial carbon uptake was only 1.9 ± 0.9 Gt C yr\textsuperscript{-1}. This CO\textsubscript{2} uptake of oceans and the terrestrial surface is termed a carbon sink due to the flux from the atmosphere to the land surface. The present sink (2006-2015) was about 55% of the emissions, i.e. almost half (45%) of the anthropogenic emissions remained in the atmosphere (4.5 ± 0.1 Gt C yr\textsuperscript{-1}). Moreover, temporal variability of these partitioned global fluxes is very high, as seen for years with considerable flux increases, closely followed by years with smaller increases (light blue and green spikes in Fig 23.8A). These fluctuations can be caused by changes in the ratio of respiration to assimilation (i.e. NEP and NBP; see Chapter 16) or fire occurrences. Years with El Niño events stand out (i.e. 1987, 1998, 2015) as years with very low terrestrial CO\textsubscript{2} sinks. For example, in 1998, the increase in atmospheric CO\textsubscript{2} concentrations approximately corresponded to the total release of CO\textsubscript{2} from fossil fuels and industry. The continents did hardly take up any CO\textsubscript{2}; only the oceans balanced the emissions from land-use change. In contrast, in 1990 with no El Niño, the Earth surface was a significant CO\textsubscript{2} sink. Overall, the contributions to the CO\textsubscript{2} emissions were mainly coal, and to a smaller extent oil and gas. LUC contributed only about 9% of the emissions during 2006-2015 (Fig. 23.8B).
Fig. 23.8 Components of the global carbon dioxide budget as a function of time. Land-use change was the main source of CO₂ emissions until about 1950. Since then, fossil fuel burning and industrial emissions dominated. A Component fluxes of CO₂ sources and sinks. B Contribution of different sources to the CO₂ emissions (Le Quéré et al. 2016 and www.globalcarbonproject.org).

Thus, the present atmospheric CO₂ concentration is not just the result of a mass balance in a specific year, but contains the history of sinks and sources of the past. The cumulative emissions since year 1870 until 2015 were caused by burning of coal (35%), oil (26%), gas (10%), burning of cement (2%), and land use change (26%). These emissions, totalling 262 ppm, were balanced by terrestrial ecosystems (see Chapter 16) as land sink (29%), and net uptake by the oceans (28%). 43% of the total CO₂ emissions since 1870, totalling 112 ppm (288 ppm in 1870, 400 ppm in 2015), remained in the atmosphere by 2015 (www.globalcarbonproject.org).

Total CO₂ emissions mainly originate from three regions of the world: Eastern USA, Europe and East Asia, and even the use of biofuel and other renewable energies did not change this pattern of emissions. Each region had a different pattern of emissions over time (Fig. 23.9A), but the increase of total CO₂ emissions from China since the year 2000 is most remarkable.
Fig. 23.9 Global distribution of CO₂ emissions and net flows of carbon embedded in commercial goods. A Total CO₂ emissions (Gt CO₂ yr⁻¹) in different regions of the world for the year 2015. Red: China, green USA, blue: Europe, and magenta: India. B Flow of carbon embedded in commercial goods and services expressed by Mt CO₂ yr⁻¹. (www.globalcarbonproject.org)

The industrial emissions of CO₂ are the result of major commercial flows of oil and of goods around the globe (Fig 23.9B). The Near East is the main producer of oil that is transported mainly to Europe, East Asia and the USA. In addition, Europe receives as much fossil energy from oil as from gas originating from Russia (fossil fuel fluxes not shown in Fig 23.9). Europe and the USA receive additional fossil fuel from Norway and Canada, respectively. The import of energy as oil to East Asia enables high industrial production of many goods, which are then exported. This results in a major net export of embedded carbon in form of these exported industrial goods from China, while Europe and the USA are net importers of embedded C. Thus, it is the demand for goods, which caused the increased emissions of China, and it is under debate if the associated emissions should be accounted for the countries of production (China) or of consumption (Europe, USA). Over the past 60 years, the emissions per capita were three times as high in the USA than in Europe and China. The decrease of the emissions per capita since about 2005 in Europe and USA was not the result of environmental policy for renewable energy, but resulted from imports of embedded carbon in products imported from China. Thus, the effective total emissions per capita have not changed in the Western World.

Parallel to the increase in CO₂ concentrations, the concentrations of methane (CH₄) and nitrous oxide (N₂O) also increased (see Chapter 21). Despite of relatively low concentrations
In the atmosphere (in the ppb range), CH$_4$ and N$_2$O are very important drivers of global warming. Biological CH$_4$ emissions are caused by microbes under anaerobic conditions and incomplete fermentation, e.g. under conditions of flooded rice cultivation, and the digestive systems of ruminants and termites, and from organic waste, incl. landfills. CH$_4$ is also produced during biomass burning, fossil fuel burning and natural leaks (Kirschke et al. 2013). Previously it was assumed that 70% of global CH$_4$ emissions would originate from biological sources and 30% from fossil fuel industry and natural geological leaks (IPCC 2013). A novel methane budget, based on stable isotopes of C and H supports this percentage but also reveals that anthropogenic CH$_4$ emissions originating from geological sources, i.e. leakage and oil and gas industries, are much larger than originally thought (Schwietzke et al. 2015). N$_2$O emissions are mainly caused by nitrification and denitrification in soils and oceans, due to natural processes and fertilisation, fossil fuel burning and biomass burning.

In addition to these trace gases, other trace gases such as stratospheric ozone-depleting halocarbons (CFCs, HCFCs) and short-lived gases like CO and NO$_x$ contribute to the radiative forcing. Also aerosols and their precursors (mineral dust, SO$_2$, NH$_3$, organic carbon, black carbon or soot) play an important role, although their impact on radiative forcing can be negative or positive. Negative effects on radiative forcing (i.e. cooling the atmosphere) result from the reflection of solar radiation by aerosols already high in the atmosphere, so radiation does not reach the ground in the first place. Positive effects on radiative forcing (i.e. warming the atmosphere) result from the absorption of radiation by aerosols and the albedo effects black carbon or soot have when deposited on surfaces, e.g. snow. Aerosols and their interactions with clouds are responsible for the largest uncertainty in the overall radiative budget estimate (IPCC 2013). One crucial aspect has been the occurrence of global dimming, observed in radiation measurements over several decades since 1950. The incoming solar radiation did gradually decrease, due to aerosols from air pollution. However, after environmental regulations were put in place and air pollution and thus aerosol levels decreased, this trend reversed: global brightening has been observed since the 1990s (Wild et al. 2007). Global dimming probably reduced the effect of increasing greenhouse gas concentrations early on. Overall, greenhouse gases contributed with about 0.5 to 1.3 K (1951 to 2010) to the global mean surface warming, while aerosols and other anthropogenic forcing contributed with about -0.6 to 0.1 K. These estimates support the observed warming of about 0.6 to 0.7 K during the same period.
The link between radiative forcing by trace gases and by aerosols and the resulting global temperature change is called \textit{climate sensitivity}. It quantifies the change in Earth temperature with increasing radiative forcing that could either be caused by changes in solar radiation or by greenhouse gases, which absorb in the infrared, and aerosols (Eq. 23.1).

\[
\Delta T_s = \lambda \text{RF}
\]

with $\Delta T_s$ indicating the change in global surface temperature, RF the radiative forcing, and $\lambda$ the climate sensitivity.

Based on geological evidence, the climate sensitivity is with high confidence 1.5 to 4.5 K per doubling of atmospheric CO$_2$ (IPCC 2013). The \textit{global warming potential} (GWP) of gases is calculated based on a time-integrated radiative forcing for 1 kg of a gas relative to the RF of a reference gas. In the case of climate change, this is CO$_2$, which has a GWP of exactly 1. The GWP of all other gases is expressed in CO$_2$-equivalents (CO$_2$-C$_{eq}$), generally estimated on a 100 year timescale to account for the lifetime of different gases. The \textbf{Intergovernmental Panel on Climate Change} (IPCC, see Chapter 23.5) has slightly changed the GWP values over the course of its different reports, and also introduced other metrics (IPCC 2013). For methane, the global warming potential (without accounting for climate-carbon feedbacks) is 28 g CO$_2$-C$_{eq}$ per g CH$_4$, and for N$_2$O it is 265 g CO$_2$-C$_{eq}$ per g N$_2$O (IPCC 2013).

One of the major tasks of the IPCC is the evaluation what effects different scenarios of increased trace gas and aerosol emissions and thus atmospheric trace gas and aerosol concentrations would have on global and regional climate in the future. The prediction of the future is difficult because the future is embedded in a socio-economic background of political and societal decisions, which are beyond any predictability. Thus, the IPCC decided to develop \textbf{Representative Concentration Pathways RCP} (Nakicenovic and Swart 2000), which are the basis for science and fact-based predictions of how climate will develop if certain emissions are maintained or changed. A temperature increase of 2 K is regarded as a critical limit. This limit is exceeded with an increase of global CO$_2$ concentrations beyond 450 ppm. In the year 2016, the global CO$_2$ concentration already exceeded 400 ppm, which is about 120 ppm above the pre-industrial CO$_2$ concentration of 280 ppm. In 2014, the temperature increase was 1 K, exceeding the temperature maximum of the past 1000 years as confirmed by tree ring analyses (LaMarche et al. 1984).
At the moment, a doubling or tripling of the pre-industrial CO₂ concentrations is predicted depending on the RCP, leading to a calculated \textbf{global temperature increase} of 3–4 K. There is a delay between increasing CO₂ concentrations and temperature because of the heat capacity of oceans (they act as a heat sink; Levitus et al. 2000) and the melting of the polar ice caps (energy required for melting). The increase in temperature will not be constant across the globe, but affect the Northern Hemisphere more than the Southern Hemisphere, the arctic and boreal regions more than the temperate and tropical zones (Fig. 23.10A). Also precipitation patterns and thus soil moisture levels are expected to change in the future (Fig. 23.10B). There is an increasing likelihood of drought in the Mediterranean Region, in the Amazon, and in Southeast Asia. Dry summers appear to move poleward, and will affect Central Europe later this century. Moreover, the observed extreme events of the past, e.g. heavy precipitation, drought and heatwaves, may increase in frequency in the future. Observations confirm a general increase in heavy precipitation events globally as expected from radiative forcing. There is medium confidence that anthropogenic influences contributed to the occurrence of droughts globally, but not at regional scale. Tropical storms appear to have moved poleward, but an increase in intensity could not be shown, even though observations suggest an increase in the intensity of tropical cyclones.

\textbf{Fig. 23.10 Predicted changes in global temperature and global soil moisture.} A Global temperature change in June, July and August comparing 2016 to 2035 relative to 1986 to 2005. B Associated changes in soil moisture. Hatched areas indicate regions where the projected changes are smaller than the internal variability by one standard deviation; stippling indicates regions where the multi-model mean projections deviate significantly from the
simulated 1986-2005 period and where at least 90% of the models agree. Thus, this are the regions, where significant changes took place over the past decade. The number of models considered in the analysis is listed at the top right hand side of the graphs (IPCC 2013).

Since the future temperature rise depends on the net budget of historic emissions, one can calculate the total amount of allowable future emissions to reach a certain climate goal. A 2 K temperature rise is reached by 1000 Gt C emission. 555 Gt C of this quota have already been emitted by 2015. 445 Gt C is left, which could be used within 40 years at the present rate of global CO₂ emissions. This would mean in reality that by 2057, no fossil fuel shall be used anymore to reach the 2 K temperature goal.

23.3.2 Responses of Terrestrial Ecosystems to Climate Change

Terrestrial ecosystems on Earth have already responded to the existing level of climate change in numerous ways, despite their capacity to resist and recover, i.e. their resilience (see Chapters 13.4, 17.4). Due to their adaptive capacity, it is most likely that not all responses are apparent yet. Furthermore, ecosystems respond to multiple factors contributing to climate change at the same time, e.g. increasing atmospheric CO₂ concentrations and air temperature (Tab. 23.3). Therefore, responses cannot be linked to one factor alone. This is only possible with dedicated experiments (see Chapter 14.2). It is also expected that ecosystems can tolerate change until a threshold is crossed (e.g. temperature extremes). Beyond this threshold, they might not be able to withstand the impact and their adaptive capacity cannot ensure their existence. As a consequence, they might transform into another state, they might lose their functioning, or change their species composition or both.

Tab. 23.3 Factors contributing to climate change as well as responses of terrestrial ecosystems and their feedbacks on the environment. The table will never be complete in terms of ecosystem responses and feedbacks on the environment, e.g. adjacent ecosystems, the atmosphere and the hydrosphere, because responses of ecosystems might be buffered and therefore delayed while at the same time affected by the magnitude of climate change.

<table>
<thead>
<tr>
<th>Factors contributing to climate change</th>
<th>Consequences for ecosystem</th>
<th>Feedbacks on environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ concentration</td>
<td>Change in ratio photosynthesis to transpiration and LAI, impacts on carbon allocation, changes of litter</td>
<td>Change in evaporative cooling, change in soil C inputs and CO₂ fluxes, migration</td>
</tr>
</tbody>
</table>
The factors of climate change to which ecosystems need to react include changes in atmospheric conditions (CO₂, O₃ and aerosol concentrations, temperature, precipitation, N deposition), but also extreme events (heatwave, drought, flood; Tab. 23.3). Many of these factors and events directly affect ecosystem biogeochemical fluxes of water, carbon and nutrients, independent if these fluxes come from plants or microorganisms (see Chapter 16), and therefore affect carbon and nutrient pools as well. This can lead to changes in ecosystem composition and biodiversity via changes in inter-specific interactions, damage and death of vegetation, or loss of species (see Chapter 20). The soil compartment plays a crucial role as

<table>
<thead>
<tr>
<th>Factor</th>
<th>Impacts on plant growth and LAI, changes in soil biogeochemistry, soil acidification, support but also damage and decline of vegetation (highly context-specific)</th>
<th>Change in biodiversity, changes in soil leaching, effects on landscape albedo and hydrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric N deposition, O₃</td>
<td></td>
<td>Changes in biodiversity, changes in soil leaching, effects on landscape albedo and hydrology</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>Change and loss of habitats, migration of species, changes in biospheric-atmospheric water and trace gas exchange,</td>
</tr>
<tr>
<td>Heat wave</td>
<td>Decrease of most biogeochemical and physiological processes, stress, damage and death of vegetation, loss of C sequestration</td>
<td>Decrease in biospheric-atmospheric trace gas exchange, change in evaporative cooling</td>
</tr>
<tr>
<td>Growing season length</td>
<td>Impacts on plant growth and LAI, changes in competition and thus biodiversity, impact on C sequestration, change in trophic interactions</td>
<td>Change in albedo, changes in biospheric-atmospheric water and trace gas exchange</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Change in ratio photosynthesis to transpiration and LAI, impacts on plant growth and carbon allocation, changes in competition and thus biodiversity, impact on C sequestration</td>
<td>Changes in biospheric-atmospheric water and trace gas exchange, migration</td>
</tr>
<tr>
<td>Drought, flood</td>
<td>Decrease of most biogeochemical and physiological processes, stress, damage and death of vegetation, loss of C sequestration</td>
<td>Decrease in biospheric-atmospheric trace gas exchange, change in evaporative cooling, change in biodiversity</td>
</tr>
<tr>
<td>Aerosols</td>
<td>Impacts on photosynthesis and growth, impacts on nutrient cycling and C sequestration</td>
<td>Effects on landscape albedo and hydrology, changes in soil leaching</td>
</tr>
</tbody>
</table>
well (Smith et al. 2016). But the responses of ecosystems are not restricted to the local scale, but also show effects on landscape or even larger scales. Any change in net ecosystem fluxes feeds back on the atmosphere and on the hydrosphere. Changes in local species composition together with climate change can trigger species migration and larger-scale biodiversity changes. These feedback and feedforward effects make understanding and dealing with climate change effects difficult and complex. Some examples will illustrate this.

**Changes in photosynthesis, biomass production and allocation:** High atmospheric CO\(_2\) concentrations have been shown to increase photosynthesis rates at leaf level (see Chapter 12) and in the short-term also at stand level (see Chapter 14). In the long-term or under resource limitations (either nutrients or water), the response to elevated CO\(_2\) diminishes (Norby and Zak 2011). **Downregulation of photosynthesis** plays an important role since stomatal aperture is reduced at high ambient CO\(_2\) concentrations to reduce transpirational losses (see Chapter 10). Thus, the ratio of photosynthesis to transpiration increases. Moreover, leaf chemistry and thus litter quality changes with developing nutrient deficiencies under elevated CO\(_2\), leading to lower decomposition rates and lower carbon sequestration potentials. On the other hand, forests use more photoassimilates for aboveground biomass production at higher nutrient availability than at low nutrient availability (58% vs. 42%; Vicca et al. 2012). This difference in allocation of up to 16% is not due to increased autotrophic respiration under high nutrient supply, but probably due to higher investment belowground for root growth and symbioses under low nutrient supply. Thus, increasing CO\(_2\) concentrations will not necessarily lead to more CO\(_2\) being assimilated. This can only happen if nitrogen and other resources are available in the long-term. However, the shift in allocation from below- towards aboveground parts makes these ecosystems more vulnerable to drought, in forests also to wind-throw.

**Change in C sequestration:** Carbon sequestration in terrestrial ecosystems is affected in different ways. Climate change factors do modulate gross primary production and thus C inputs into the ecosystem, but also autotrophic as well as heterotrophic respiration and thus C loss from ecosystems (see Chapter 16). Based on ecosystem flux measurements, it has been shown that assimilation is more susceptible to drought than respiration at the ecosystem level (Schwalm et al. 2010). Thus, depending on the relation between gains and losses, the ecosystem CO\(_2\) flux budget will change.
Forest decline, tree mortality, and forest die-off: Forest decline had been of major concern across the Northern Hemisphere in the 1970ies and 1980ies (see Chapters 11, 16), and this has been recognised as an interaction of nutrient effects. Acid rain from SO$_2$ resulted in an acidification of soils, and a decrease in cation availability, while nitrogen availability from wet and dry deposition increased and accelerated tree growth. Thus, trees died from a nutrient imbalance. This phenomenon disappeared with scrubbing of smoke from power stations, with liming agricultural and forest soils in Europe and North America as well as thinning of declining forests. Since then, many forests recovered.

In the past decades, decreased forest performance and increased forest death have been observed world-wide due to the occurrence of climate extremes during the growing season. Examples range from direct effects, as during the heat wave across Central Europe in 2003 (Ciais et al. 2005), to combined effects, as the tree mortality due to drought after beetle outbreaks and associated viral and fungal infections in North America. The simultaneous occurrence of heat and drought or drought and insect outbreaks results in complex interactions. During the heat wave in 2003, gross primary production (GPP) and ecosystem respiration in forests were both negatively affected. Because respiration was more affected than GPP, net ecosystem productivity of European forests turned from a C sink into a C source. The equivalence of five years of C sink was lost in a few weeks of an extreme weather event. Different ecosystem types react very differently to severe drought events. While grasslands keep up both GPP and ecosystem water vapour fluxes (ET) for quite some time into a drought period, forests react almost immediately to a drought by decreasing ET. This pattern changes when the drought is on-going for longer: the grassland vegetation dies off, while the forests continue to photosynthesise and transpire (see Chapter 16.1). Thus, evaporative cooling of the atmosphere by the biosphere is highly dynamic and strongly related to landscape heterogeneity, i.e. the fraction of forest to grassland vegetation. The impact of drought and heat waves on forests can be aggravated when bark beetles carry virus and fungi infections. The beetles are specialised in attacking weakened tree individuals and are capable to use a prolonged and warm growing season for several generations in one year (see Chapter 13.5, Box 13.1). These beetle populations can then attack also healthy trees. Whole landscapes with forest vegetation may change into open woodlands within a couple of years (Allen et al. 2015). Also other extremes, such as the combination of heat and ozone, could affect ecosystem and human health.
**Spring advancement and increased growing season length:** Earlier unfolding of leaves (also called spring advancement) as well as earlier nesting of birds or arrival of migrant birds and butterflies have been prime observations in the Northern hemisphere (Parmesan and Yohe 2003; Peñuelas et al. 2009). Globally, spring events advanced by 2.3 days per decade over the last 130 years, with considerable variation among ecosystem types (up to 14 days per decade for boreal ecosystems). Range shifts of about 6 km per decade northward or 6 m per decade upward have been reported (Parmesan and Yohe 2003). Leaf unfolding dates in Europe were negatively correlated across a large number of woody species with the pre-season temperature (-0.61±0.61, Fu et al. 2015). Not only woody species but also herbaceous plants respond with earlier leafing out. However, the advance of un-folding declined from 3.4 days K\(^{-1}\) during the period from 1980 to 1994 down to 2.3 days K\(^{-1}\) during the period 1999 to 2013. This decline in response to spring warming could not be explained by chilling periods in early spring, but were explained by the fact that other mechanisms may interact, such as the photoperiod. Even with further warming, leaves will not unfold in winter because of the shorter photoperiod. This would give an advantage to evergreen conifers or to winter-green herbaceous crops (winter wheat) which assimilate CO\(_2\) whenever temperatures are suitable. Richardson et al. (2013) reviewed the interactions of phenology and climate change, also focussing on feedback and feedforward processes. Increases in annual GPP with longer growing season length are well supported by eddy-covariance flux measurements (see Chapters 14, 16). However, this does not necessarily increase overall net ecosystem productivity. With increasing autumn temperatures, also respiratory losses increase, at least in northern ecosystems (Piao et al. 2009), compensating higher spring or annual GPP. This seems to be due to enhanced soil respiration (Gonsamo et al. 2017).

The length of the growing season is not only determined by unfolding, but also by leaf senescence in autumn. It emerges that also leaf fall is delayed, but the response is species specific. While some broad-leaved species show leaf senescence with change in leaf colour in autumn (*Fagus, Acer*), other species (*Fraxinus, Alnus*) keep green leaves until a first frost kills the leaves. Nevertheless, with warmer autumns, also leaf fall has been delayed. An increased growing season length of 2.1 to 42 days per decade has been reported for temperate forests in Europe and North America (Richardson et al. 2013). For crops, the frost-free days have decreased since 1975 until 2010 at a rate of -0.8 to -0.4 days per year in Northern, Eastern and Central Europe, but showed little or no change in the Mediterranean region (European Environmental Agency 2017).
23.3.3 Feedbacks of Terrestrial Ecosystems on Climate

Terrestrial ecosystems are not only affected by climate change and show multiple responses to changes in the atmosphere (see Chapter 23), but they also exhibit numerous feedbacks with which ecosystems affect the climate (see Tab. 23.3). These feedbacks can also be considered as emergent properties of ecosystems (defined in Chapter 13). Some selected examples will illustrate these feedbacks.

**Temperature sensitivity of the carbon dioxide cycle:** Any change in ecosystem C sequestration is related to changing proportions of assimilation to respiration. But these processes have feedbacks on the atmosphere, in particular on decomposition and soil organic matter formation (see Chapter 16). Decomposition of plant material is stimulated by increasing temperatures and litter fall (but decreased by low litter quality). A value of 7.7 ppm CO₂ per 1 K has recently been suggested as carbon cycle climate sensitivity for the Northern hemisphere, i.e. the additional CO₂ emission due to such a temperature feedback (Frank et al. 2010). However, it remains unclear if respiration will acclimate and decline again in relation to the available substrate.

**Net greenhouse gas budgets:** The net uptake of carbon dioxide from the atmosphere and its sequestration in soils and woody biomass are among the main processes considered for climate mitigation. In addition, reductions of CH₄ and N₂O emissions, particularly from agriculture, are discussed. Assessing full greenhouse gas (GHG) budgets require not only flux measurements of these gases (see Chapters 14, 16), but also the compilation of further data on C inputs and exports to calculate the net biome production (see Chapter 16). In addition, CH₄ and N₂O fluxes need to be considered to calculate the net greenhouse gas budget (NGB). Using the European GHG budget as an example (Fig. 23.11; Schulze et al. 2009, 2012), forests, grasslands and croplands are compared, which form the highly heterogeneous European landscape. At the level of gross primary production, the three land use types do not differ, since the availability of light mainly limits this process. Differences in metabolic rates are compensated by differences in growing season length and plant structures. At the level of net primary production, grasslands have higher flux rates than forests or croplands, but most of this production is either harvested for animal feed or grazed. Harvest removals are similarly high for croplands. But also forests are eventually harvested or fall to
the ground after disturbances. Restricting the Net Biome Production (NBP) calculation to biomass (NBP\textsubscript{Biomass} in Fig. 23.10), results in highest accumulation of carbon in forests (here: negative NBP means C uptake), but it depends on the present age structure of forests in Europe. This large capacity of forests to accumulate carbon in (mainly woody) biomass of growing stands and in soils is the basis to promote afforestation programs in the context of climate mitigation. Moreover, grasslands are mainly used as feed for ruminants, which emit CH\textsubscript{4}, and both grasslands and croplands are fertilised and typically emit N\textsubscript{2}O. Thus, fluxes of these other GHGs must be considered as well. The resultant net greenhouse gas balance (NGB total) shows that forests remove more GHG from the atmosphere (negative sign) than grasslands and croplands. The overall total NGB for all three European land-use types is carbon neutral.

Fig. 23.11 The net greenhouse gas budgets (NGB) for different land use types in Europe. All three greenhouse gases (GHG) CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O are considered as CO\textsubscript{2}-C-equivalents. NGB are given for soils (NGB Soil) and for the entire ecosystem (NGB Total). Negative numbers give GHG sinks, positive numbers GHG sources. GPP (negative number) is equilibrated by the losses (arrows pointing upward) and gain of manure to result in NGB.
NGB is composed (arrows pointing downward) by changes in biomass, NBP and NGBsoil. Numbers in brackets represent 1 standard deviation. GHG losses are depicted with arrows pointing upward, GHG gains with arrows pointing downward. DOC and DIC stand for dissolved organic and inorganic carbon, respectively (after Schulze et al. 2009).

**Fossil fuel substitution** has been suggested as a major mechanism to support climate mitigation. Biomass use for **bioenergy** (including methane production and liquid biofuels) has been state-supported even though biofuel production using agricultural crops competes with food and feed production. Also fertilisation of bioenergy crops produces N$_2$O, and the land area for production of oil, such as oil-palm or soybean, competes with natural vegetation (Haberl et al. 2012). The energy shortage in Europe in the 19th century before fossil energy (mainly coal) was available may be taken as an indication of the limitations of biomass production to mitigate fossil fuel use. Nevertheless, the use of biomass for energy after a chain of utilisations appears still to be an important contribution to climate mitigation.

**Bioeconomy** is an additional venue to replace fossil fuels where any components in daily life shall be biomass based (e.g. production of plastics). This will increase the demand for biomass in the future, and it is not clear where this biomass shall be produced (Canadell and Schulze 2014).

**Evapotranspiration:** Evapotranspiration of the land surface is an additional major factor contributing to cooling of the atmosphere as explained above (see Chapter 16.1). It has thus been hypothesised that the destruction of the rainforest in the Amazon basin would result in a warmer and drier climate (Bonan et al. 1992). However, this remains a hypothesis. On the other hand, grasslands can have even higher rates of evapotranspiration than forests, particularly early into a drought (see example given above). This contributes to atmospheric cooling and can promote regional rainfall. This behaviour reverses with longer drought periods and after harvests. During longer droughts, forests remain the main source of water vapour fluxes (see Chapter 16.1; Teuling et al. 2010). Moreover, harvested fields have low evapotranspiration rates, and dissipate a lot of sensible heat. When warm air-masses move across heterogeneous landscapes (with agriculture, forest and urban land use), this increases the evapotranspiration from forests. The then hot and moist air masses contribute to convective thunderstorms and hail, and may cause extreme events over cities that are heat islands in the landscape.
Albedo: These negative effects of forest evapotranspiration on the radiative forcing reverse in the boreal and arctic zones, where the northward progression of forest not only increases carbon storage, but also changes the albedo of the landscape, especially in winter (see Chapter 9). The dark tree crowns reduce the reflectivity of snow, from >0.5 over snow to <0.15 over forests. This leads to warmer winter temperatures (Bonan 2008). Thus, high-latitude afforestation will accelerate rather than mitigate climate change (Bala et al. 2007).

23.4 Changes in Biodiversity

Diversity of species is the main variable available for an assessment of changes in biodiversity at global scale (see Chapter 20.2). Most often, vascular plant species are used, sometimes birds and certain insect groups are included. However, no information is available about the diversity of microorganisms at the global scale. Further indicators closely rely to species information, such as extinction risks, habitat extent, or community composition.

Considering the world map of plant distribution (see Chapter 20.3, Fig. 20.11), there are 35 so-called biodiversity hot spots (Fig. 23.12) – regions with very high plant diversity and high level of endemism (>1500 endemic species/hot spot), and where 70% of the habitat are already lost. In addition, there are genetic centres of crop species, also called Vavilow centres. Both regions overlap only partially. It has been estimated that the species hotspots cover about 16% and the hotspots of crops about 8% of the Earth's surface in the past (Cincotta et al. 2000). Currently, about 1.1 billion people live within those biodiversity hotspots, covering about 2.5% of the Earth's surface. If it were possible to protect these hotspot areas from further land-use change today, it would be possible to protect 50% of global plant species as well as 42% of birds, mammals, reptiles and amphibians (Myers et al. 2000).
Biodiversity loss is tightly linked to several aspects of human land use, resulting in direct removal of species or habitat degradation and loss. Currently, the “big killers” are overexploitation (LUC, hunting, fishing), agricultural activities (crop and livestock farming, timber plantations), and urban development (housing, tourism, traffic). Other important drivers of biodiversity loss are invasive species and diseases, pollution (pesticides, wastes, N deposition and eutrophication), climate change and system modifications, such as increasing fire frequency and dam constructions (Maxwell et al. 2016). Climate change is negatively affecting biodiversity through storms and flooding, habitat modification, extreme temperatures and drought (see also Table 23.2). Simulations suggest that with an increase of global temperatures by 4 K in 2100, more than 500 plant species per grid cells of 110 x 110 km could be lost, mainly in tropical and subtropical regions (Sommer et al. 2010). Climate change will cause extinctions if species cannot adapt to the new environmental conditions, or if their dispersal capacities will not allow them to migrate to sites with adequate conditions. Because the range of dispersal mechanisms is very large (see Chapter 18.2), even within vegetation types, the distribution of plant species will change considerably: some species may keep pace with climatic change, while others may lag behind, resulting in new combinations and associations of species. Such spatial shifts may occur over hundreds of kilometres, but also within very short distances: for example, the large spatial heterogeneity in growing
conditions within alpine ecosystems allow species to migrate to suitable growing conditions within few centimetres (see Chapter 20.3, Fig. 20.13). Beside such range shifts, species may also respond by shifting their climatic niche through temporal changes (shifts in phenology), or internal plastic changes (shifts in physiology; Bellard et al. 2012).

Land use change is expected to stay the most important driver for biodiversity loss until the end of the century, followed by climate change, N deposition, biotic exchange, and elevated CO$_2$ concentration (Sala et al. 2000). Most indicators to evaluate the state of global biodiversity show decreasing trends while many drivers for biodiversity, e.g. resource use, invasive alien species, N pollution, overexploitation, and climate change impacts showed increasing trends (Butchart et al. 2010). Concerning land use and land-use change, the effect of intensified and extended agriculture on the diversity of species can be seen worldwide. It is a direct consequence of increasing human populations and of changes in diets, e.g. increased meat consumption, which requires more animal feed. With the current rise in human population and human activities, the scope for reducing agricultural expansion or for stabilising and protecting climate seems rather very limited.

Presently, about 50% of the terrestrial ice-free surface of the globe is intensively used by humans for crops, grazing, forestry and urban development (Fig. 23.13A; Canadell and Schulze 2014). The remaining area is either too remote or of low productivity and thus only extensively used or un-used. 4.7% of the land area is presently under protection. These numbers will change in the future (Fig. 23.13B). Assuming a high land demand, a scenario based on the implementation of a global bioeconomy and increasing living standards, and un-regulated LUC, the human appropriation of land for intensive use might increase to up to 90% of the land surface. The area of protected regions might even increase to about 8%. Nevertheless, such a scenario implies a major loss of species in the near future.
However, besides the negative perspectives for biodiversity, there are also positive aspects:

- Low diversity does not necessarily mean lower productivity. Generally, a rise of productivity is being observed with increasing species number under similar environmental conditions (see Chapter 20.4). However, the deliberate selection of highly productive species may result in higher yields than in mixed communities. Most agricultural systems rely on this principle. In forestry, few managed species such as *Eucalyptus* and *Pseudotsuga menziesii* can have a productivity a magnitude higher than other tree species or mixed forests (Fig. 23.14A), even though there is a higher risk of disturbance and a change of habitat function in mono-specific stands. Thus, potentially it would be possible to increase productivity on confined areas, which would release the pressure of land-use change on other areas. For example, 73 Mio hectares of well-managed plantations with a productivity of 25 m³ ha⁻¹ yr⁻¹ would ensure the current global need for industrial round timber, corresponding to only 2% of the global forest area (Seppälä 2007). With appropriate land use, the partitioning of global land could also maintain a large fraction of protected and endangered habitats (Fig. 23.14B).
Fig. 23.14 Productivity-diversity relationship for forests, including managed species and
the partitioning of land with appropriate management. A Productivity of natural forests,
under conditions of self-thinning, as related to tree species richness (blue band; from Liang et
al. 2015), and productivity of managed forests (red line) in various locations and with
associated species (from Liang et al. 2015, supplement). B Predicted land use in 2050 at low
land demand, assuming high intensity management on productive land (from Canadell and
Schulze 2014). The remaining unmanaged unavailable lands are mainly alpine and arctic
regions, and bogs. The unmanaged remote lands are mainly remote boreal forests.

- **Extensive land use** can actually create large heterogeneity in environmental conditions,
sometimes allowing more species to co-exist than in the pristine ecosystems that have been
replaced. The example of traditional agricultural landscapes with high plant species
diversity has already been discussed in Chapter 17.2. Several species, which rely on human
disturbances, e.g. the segetal flora (species growing in cultivated fields), are now
considered endangered and are protected. Sustainably managed forests do not necessarily
differ from protected forest in their species composition (Paillet et al. 2009).

- **Intensive land use** creates a larger number of newly evolving species, such as apomictic
or pesticide resistant species (e.g. Anthony et al. 1998). The genus of *Rubus* has been a
well investigated example (Sochor et al. 2015).

- **Nature conservation** efforts can result in successful protection of populations and species,
if the driver of endangerment can effectively be stopped, e.g. by changing management or
by protection of large or small areas, even though the protection of geographically
confined sites may not be a solution under conditions of climate change and species migration. The so-called “blue species lists” in Switzerland (Gigon et al. 1998), for instance, compile such examples of positive developments of endangered species population sizes.

There are numerous additional interactions of global change and biodiversity, such as changes in pollination (e.g. Klein et al. 2007; Potts et al. 2010) and invasions of new species (Mooney and Hobbs 2000), where the combined effects of land use and climate change drivers can result in a weakening of the resilience of existing plant communities and ecosystems (see Chapter 17.4). This in turn opens the opportunities for invasion by pests and diseases, and by alien plant species. About 20% of the 64 Central European tree species are affected by modern diseases and by old, but increasingly aggressive diseases. This can even lead to the fact that some species face extinction (Ulmus, Fraxinus). Thus, there is room for new species invading from outside (e.g. Mooney and Hobbs 2000). Therefore, alien and invasive species are often regarded as a kind of “pest” that needs to be eliminated, e.g. Pseudotsuga in Fagus forests of Europe. But one can also take an opposite view, namely that alien species take niches in communities that were opened by human management or by global climate change. Thus, the invaders in fact complement the species assembly and maintain ecosystem functioning, creating “novel ecosystems” (Hobbs et al. 2009).

Thus, with global change, the world will be different from that of present times. What the net effect will be between loss of species and the evolution of novel species, time will show. However, although current estimates of future biodiversity changes are still variable, the majority of models predict substantial negative consequences for global biodiversity, leading to extinction of species (Bellard et al. 2012).

23.5 Global Agreements to Address Global Ecological Challenges

It is clear from the foregoing chapters that it is beyond the scope of a single nation to solve the problems of climate change, loss of biodiversity, degradation of soil, etc. Therefore, these global issues were discussed at the United Nations Conference on Environment and Development (UNCED) in 1992 in Rio de Janeiro, Brazil, also called the Earth Summit. Three important conventions were signed:

- the **Framework Convention on Climate Change (UNFCCC)**,
• the Convention on Biological Diversity (UNCBD),
• the Convention to Combat Desertification (UNCCD).

An international agreement to protect forests was not passed because of conflicting interests, and this remains an unresolved issue until today.

23.5.1 Biological Diversity

The Convention on Biological Diversity (CBD, www.cbd.int), a result of the 1992 Earth Summit in Rio and meanwhile signed by 196 member states, has nearly global coverage, the USA being the most prominent non-member. Administratively hosted by UNEP, the United Nations Environmental Programme, it is acknowledged as the leading treaty in the field of biodiversity with other treaties taking over specific tasks, like the Ramsar Convention for the conservation of wetlands or the Convention on International Trade in Endangered Species (CITES) for trade related issues. The CBD defines biological diversity as the diversity of ecosystems, the diversity of species and the genetic diversity within species. It pursues three overarching goals:

• the conservation of biological diversity,
• the sustainable use of the components of biological diversity, and
• the fair and equitable sharing of benefits resulting from the use of genetic diversity.

Member states are obliged to develop national biodiversity strategies and actions plans setting their own national targets and priorities, and 185 states out of the 196 members have done so. This in itself is a big success, considering the situation in 1992 when the CBD was signed, when no state had such a strategy, and most states did not even have a ministry for the environment.

In order to structure its work, the CBD has developed a set of thematic work programs for certain types of ecosystems (e.g. marine and coastal ecosystems, mountain ecosystems, forests) and cross-cutting work programs for issues like e.g. sustainable use, invasive alien species or protected areas. Furthermore, two internationally binding protocols have been developed by the CBD, ratified and signed by member states, which now are obliged to implement them:
• since 2003, the Cartagena Protocol on Biosafety (170 member states), which regulates safe handling, transport and use of living genetically modified organisms (LMOs), and,

• since 2014, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits arising from their Utilisation (96 member states).

The CBD is an “Agreement under International Law” which in Article 3 declares that “States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, …” (United Nations 1992). This means that all organisms, which are naturally living in a country are now the property of that country and cannot be taken away or used without permission by the state. This holds also for research that is defined as use of biological materials (termed “genetic resources”, GR). The Nagoya Protocol, determining the framework for the third aim of the CBD “Access and Benefit Sharing”, encourages under Article 8 the member states to support biodiversity research on their GR and in particular for non-commercially motivated, basic research. However, it belongs to the states’ sovereignty to follow that advice or not. One of the major efforts inexplicitly expressed in the Nagoya Protocol is the endeavour to act against biopiracy and to share commercial gains between the country and the producer of a commodity. For basic research, other benefits can be envisaged such as capacity building or the development of biological collections and databases. Following the rules and standards of the Nagoya Protocol in projects even of basic research takes more preparatory time and administrative expenditure.

The CBD had set itself the target until 2010 to significantly reduce the rate of loss of biodiversity. However, in a stocktaking exercise (Secretariat of the Convention on Biological Diversity 2010), the CBD had to admit that this target has not been reached and biodiversity loss in most ecosystems is ongoing. Therefore, in 2010, the CBD adopted a new strategic plan with 20 clearly defined targets to be reached until 2020, the so-called Aichi Targets (named after the province in Japan where the respective Conference of the Parties, called COP, took place). These targets, inter alia, specify that:

• The rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced (target 5).

• Areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity (target 7).
• Pollution, including from excess nutrients, has been brought to levels that are not
detrimental to ecosystem function and biodiversity (target 8).
• Invasive alien species and pathways are identified and prioritised, priority species are
controlled or eradicated, and measures are in place to manage pathways to prevent their
introduction and establishment (target 9).
• The extinction of known threatened species has been prevented and their conservation
status, particularly of those most in decline, has been improved and sustained (target 12).

An intermediate overview (Secretariat of the Convention on Biological Diversity 2014) in
2014 showed that progress is made under most of the 20 targets, but that current ambition and
implementation speed shown by member states is not sufficient to reach the targets by 2020.

To strengthen the relations between science and policy for biodiversity issues and ecosystem
services an “Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem
Services” (IPBES, www.ipbes.net), was founded in 2012 under the auspices of four United
Nations entities: UNEP, UNESCO, FAO and UNDP. Its task is the ongoing assessment of the
state of biodiversity and of the ecosystem services, like that of the IPCC (Intergovernmental
Panel on Climate Change) for climate (see Chapter 23.2). One thousand scientists from all
over the world currently contribute to the work of IPBES on a voluntary basis. The IPBES
assessments shall be used by decision makers for the conservation and sustainable use of
biodiversity, long-term human well-being and sustainable development. A first thematic
assessment on pollinators, pollination and food production was published in 2016, including a
summary for policy makers with a set of key messages. It was the CBD who had requested
IPBES to produce such assessments and consequently these key messages where taken up by
CBD at the 13th Conference of the Parties (COP) in 2016. The COP is the Convention’s
ultimate authority that meets every two years. The messages were transformed into a decision,
encouraging CBD member states to take steps to implement concrete measures accordingly.

Although the CBD is a legally binding international agreement, it allows member states to
implement measures and programs under national priorities and with respect to national
circumstances, and there is no sanctioning mechanism in the CBD. In other words, the CBD
cannot enforce implementation in its member states, but it is the responsibility of states
themselves to take appropriate steps to reach the targets set on a global stage. Thus, the Aichi
Targets to halt biodiversity loss have a similar status as the 2°C goal negotiated with the Paris
Agreement of the UNFCCC (see Chapter 23.5.2), and both these international targets depend on the implementation by the individual member states.

23.5.2 Climate Change

The statement of the IPCC (1996) that "a recognisable influence of man on global climate" exists resulted in the so-called Kyoto Protocol as part of United Nations (1998). This protocol anticipated a legally binding obligation to reduce the emission of six greenhouse gases (CO$_2$, CH$_4$, N$_2$O, CFCs, PFCs, SF$_6$), on average by 5.2% below the level of 1990 within the period from 2008 to 2012. The European Union (EU) as a whole promised a reduction of 8%, Germany a reduction of 21%. The obligation to reduce emissions was signed by the 30 so-called Annex I states, i.e. industrial nations and states in transition to a market economy. The other 159 nations of the UN, including the USA and China, did not agree to such obligations, despite their large share to total global CO$_2$ emissions (Fig. 23.15).

Fig. 23.15 The spatial distribution of CO$_2$ emissions across the globe in 2015. The size of the circles is proportional to the magnitude of CO$_2$ emissions (http://globalcarbonatlas.org/en/CO2-emissions)

In order to achieve the reduction commitment not only by industrial activities, the Kyoto Protocol, for the first time, also considered an enhancement of biological sinks. The idea was to incorporate biological processes into the calculations, based on the fact that the obligation
for a 5.2% reduction was only a fraction of the natural CO₂ fluxes of assimilation and respiration, and that a slight change in these fluxes would compensate the obligations for reduction to a large extent.

The following measures were considered in the Kyoto Protocol:
- to enhance technical measures to reduce emissions,
- to increase biological sinks in forests by promoting afforestation and avoiding clearing,
- to establish emission reducing measures, e.g. in agriculture,
- to trade with emission certificates between industrial nations, and
- to establish projects in developing countries to increase sinks and to reduce emission (Clean Development Mechanism CDM).

The ecological effects of the Kyoto protocol were discussed in the IPCC report on changes in land use and forestry (Watson et al. 2000). The problems were:
- the forest definition (forests are stands with trees greater than 0.5 ha, 2 m in height and with 10% cover) did not protect against degradation (over-use) of forests. Emissions resulting from degradation were not credited;
- the absence of a possibility to account for protection of primary, natural forests. These were not regarded as an "anthropogenic" sink, because they did not experience any management and thus would not be credited;
- the "non-creditability" of sustainable forest management where the harvest corresponds to the increase of biomass in younger stands and replaces fossil fuel use. Changing forests into other forms of use (deforestation) was considered as emission, while harvesting prior to land-use change was not taken into account;
- the support for forest plantations with fast-growing tree species, which very often are alien to the natural flora (Eucalyptus plantations in Portugal, Pinus radiata plantations in Chile and New Zealand, etc.). In these plantations, only the increase in stem volume was countable, but not the net ecosystem production (see Chapter 16.2), also accounting for soil C losses due to intensive cultivation;
- the food, feed and wood trade from developing to developed nations with simultaneous afforestation (which was credited) and even increased forest conservation in these industrialised nations (leakage). As the areas required in developing countries were often made available by clearing primary forests, this triggered emissions and not a global C
sink. By not incorporating forestry and relocation of production to developing nations, many possibilities became available for crediting additional anthropogenic sinks, but without taking into account related emissions.

In view of these shortcomings, a new protocol for decreasing greenhouse gas emissions, adaptation and financing was discussed at the Paris meeting of the UNFCCC in 2015. A new agreement was formulated (Paris Agreement; United Nations 2015) which was signed by most nations of the UN, including the USA and China. By March 2017, the agreement was signed by 194 nations and ratified by 141. Thus, the Paris Agreement entered into force in November 2016. It was agreed that global temperatures should not increase more than 2 K and preferentially not more than 1.5 K above preindustrial level, but no binding measures were included. Each nation is free to decide how to decrease emissions. One major change compared to the Kyoto Protocol was the inclusion of forest products into the mechanisms of mitigation. In addition, a regular “stock taking” of global implementation mechanism was agreed on. Emission reductions are to be achieved without threatening food production. It will be interesting to see if this very free agreement will have an effect within the next decades.

Summary

- Global change is the sum of changes in land-use and climate which affect not only biodiversity but also many other processes. The effects of Homo sapiens have reached a level that a new geological epoch, the “Anthropocene” is under discussion. Humans affect the globe not only by their population but mainly by the intensity of their activities.

- We distinguish land use of variable intensity where the land cover is not changed, and land-use change, which is a change in the way the land is used. In addition, land cover describes the cover of the Earth’s land as vegetation or man-made feature. Land-use change has mainly affected forests for the creation of agricultural land (cropland, grassland).

- The production of food, feed and energy dominates land use. Only few regions of the world (Europe, temperate North America, and East Asia) supply the necessary food for 9 billion people. In addition, there are major flows of biomass between continents mainly to supply the needs of the developed world, and the flow of industrial goods, which contain “embedded carbon” due to the energy cost for production in the land that produced these goods.
Climate change is a major component of global change. It is mainly caused by the burning of fossil fuels for energy. Land-use change contributes about 10% to the total emissions of 10 Gt C yr\(^{-1}\). 26% of the emissions are balanced by ocean uptake, and 31% by the net uptake of terrestrial ecosystems. 43% remain in the atmosphere. This results in a change of the physical properties of the atmosphere and thus in global warming. The physical properties of the atmosphere are additionally changed by emissions of N\(_2\)O, originating mainly from incomplete decomposition and from incomplete N\(_2\) fixation, and by emissions of CH\(_4\), resulting from mining fossil fuels and from anaerobic processes during decomposition and enteric fermentation. At this moment, all continents and all climatic regions of the world are affected by global climate change.

The factors contributing to climate change are increased greenhouse gas concentrations, warmer temperatures and longer growing seasons, occurrence of climatic extremes (heat waves, droughts), but also changes in precipitation patterns. Terrestrial ecosystems respond to these factors by changes in production and allocation, but also by decline and mortality. In addition, competition and species composition change as well as biogeochemical processes.

These changes of terrestrial ecosystems have profound feedbacks to neighbouring ecosystems and the atmosphere. These include changes in the rate of respiration, but also other greenhouse gas emissions. Evapotranspiration as well as changes in albedo have profound effects on the energy budgets of the Earth’s surface.

The establishment of net greenhouse gas budgets is a major task for science in order to ascertain that major processes that may affect climate are not overlooked. Despite of its high ecosystem production, Europe is about C neutral due to its high emissions of CH\(_4\) and N\(_2\)O. Mitigation of climate change is expected from the use of biomass for bioenergy and bioeconomy, which shall replace fossil fuel-based products.

Global change has resulted in major changes of biodiversity and the provisioning of ecosystem services. Biodiversity hotspots and genetic diversity centres are under threat. It is expected that with further land-use change, these effects will increase in the future. One solution being discussed is the use of high yielding crops and forest species to alleviate the pressure from natural systems.

Global agreements such as the Convention on Biological Diversity (UNCBD), the Framework Convention on Climate Change (UNFCCC) and the Convention to Combat Desertification (UNCBD) have been negotiated internationally to address these problems.
Although the pressures are high, progress is still rather slow. Major achievements are the Aichi Targets (CBD) and the Paris agreement (UNFCCC).

References


