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Abstract
The future bioeconomy is expected to drive the transition towards a more sustainable economy by addressing some of the major global challenges, including food security, climate change and resource scarcity. The globally increasing demand for food in particular, but also materials and renewable energy, necessitates innovative developments in the primary sectors. Innovations will need to generate more resource-use-efficient technologies and methods for increasing productivity in agriculture, forestry and aquaculture without jeopardizing the Earth's carrying capacity and biodiversity. The bioeconomy exploits new resources by building on renewable biomass. Through this, the introduction of innovative and resource-use-efficient production technologies and the transition to a sustainable society, it helps to substitute or reduce the use of limited fossil resources, thereby contributing to climate change mitigation.

Keywords
Climate change • Natural resources • Planetary boundaries • Population growth • Food security • Global challenges

Learning Objectives
In this chapter you will:

- Get an overview of the main challenges of the twenty-first century.
- Identify the interrelations between the causes of these challenges.
- Understand how the bioeconomy can contribute to meeting these challenges.

In the course of 1 year, the Earth travels 940 million km around the sun, from which it receives 1366 W/m^2 of solar radiation (2,500,000 EJ per year). Of this, 0.25% is transformed into usable biomass through the process of photosynthesis. The Earth's vegetation sequesters about 175 petagrams (175,000,000,000,000 kg) of carbon a year, equivalent to about 300,000 billion tons of biomass (Welp et al. 2011).

Before humankind discovered fossil oil, coal, gas and uranium and learnt how to put them into use, biomass covered all human needs for food, energy and materials.

2.1 Fossil Resources and Climate Change

The use of fossil resources fuelled industrialization, which was driven by technical and economic processes causing a shift from mainly agrarian towards industrial production. However, the availability of fossil resources is limited and its use resulted in negative environmental effects.

There are an estimated 37,934 EJ of fossil energy reserves and 551,813 EJ of fossil energy resources globally (Fig. 2.1, BGR 2015). Reserves are the amounts of energy sources that have been determined with high accuracy and are economically exploitable. Resources are the amounts of an energy resource for which there is geological evidence, but which are

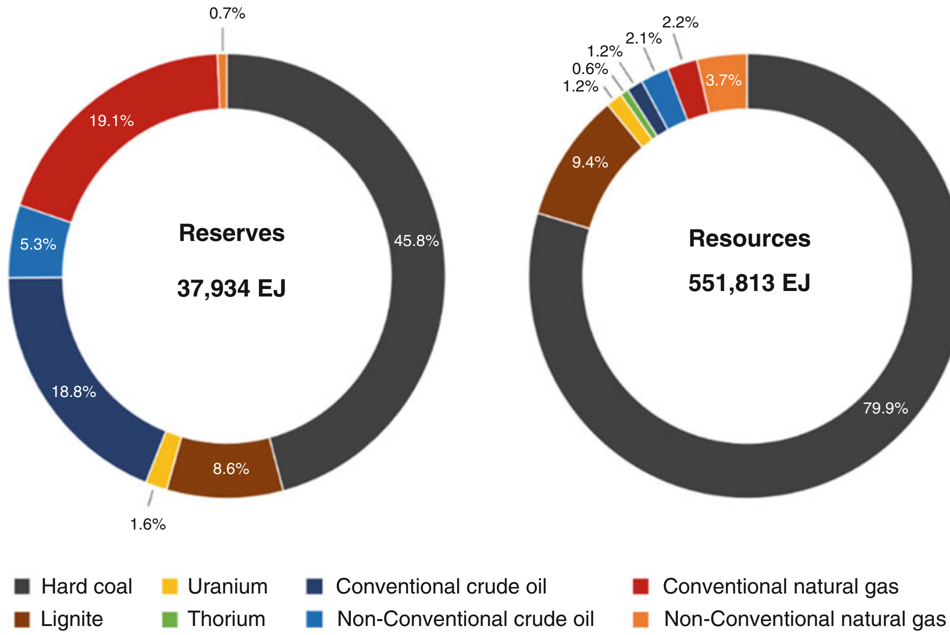

Fig. 2.1 Fossil reserves and resources, determined for 2014 (BGR 2015)

either economically or geologically not exploitable. Currently, fossil energy reserves exceed the global primary energy consumption of 540 EJ 70 times. However, crude oil, which is also required for material uses, makes up only 24% of fossil reserves (BGR 2015) and is therefore expected to be the first fossil resource to deplete.

Fossil Resources
Fossil resources include coal, petroleum, natural gas, oil shales, bitumens, tar sands and heavy oils. All contain carbon and were formed as a result of geological processes acting on the remains of organic matter produced by photosynthesis (see Sect. 5.1.1), a process that began in the Archean Eon more than 3 billion years ago. Most carbonaceous material occurring before the Devonian Period (approximately 415 million years ago) was derived from algae and bacteria (https://www.britannica.com/science/fossil-fuel).

Fossil resources were formed from biomass through geological processes that occurred several million to billion years ago. For this reason, they have a high carbon content (see Table 2.1). With every ton of fossil oil or coal burnt and transformed to energy, about 0.8 tons of carbon are oxidized, and 3 tons of carbon dioxide (CO_2) are released into the atmosphere (Table 2.1).

The atmospheric concentrations of the major greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have shown increases of 40%, 150% and 20%, respectively, since the year 1750 (IPCC 2014). These increases are mainly driven by the combustion of fossil fuels, deforestation and soilborne greenhouse gas emissions. Between 1970 and 2010, CO_2 emissions from fossil fuel combustion and industrial processes accounted for the largest share (78%) of the increase in GHG emissions (IPCC 2014). Today, electricity and heat production, industry and land-use-related activities (agriculture, forestry, land use change) are the sectors that contribute most to the so-called global warming potential (GWP), which is expressed in CO_2 equivalents

Table 2.1 Carbon contents of fossil resources and amounts of carbon dioxide (CO_2) and other greenhouse gases (GHG) emitted when fossil fuels are used energetically

Fossil resource	% carbon (C)[a]	Greenhouse gas emission (t/t)[b]		
		CO_2	N_2O	CH_4
Hard coal	71.6	2.6	0.000027	0.000040
Lignite	32.8	1.2	0.000012	0.000018
Petroleum	84.8	3.1	0.000127	0.000025
Natural gas	73.4	2.7	0.000048	0.000005

[a]IPCC (2006)
[b]Authors' own calculation based on IPCC (2006)

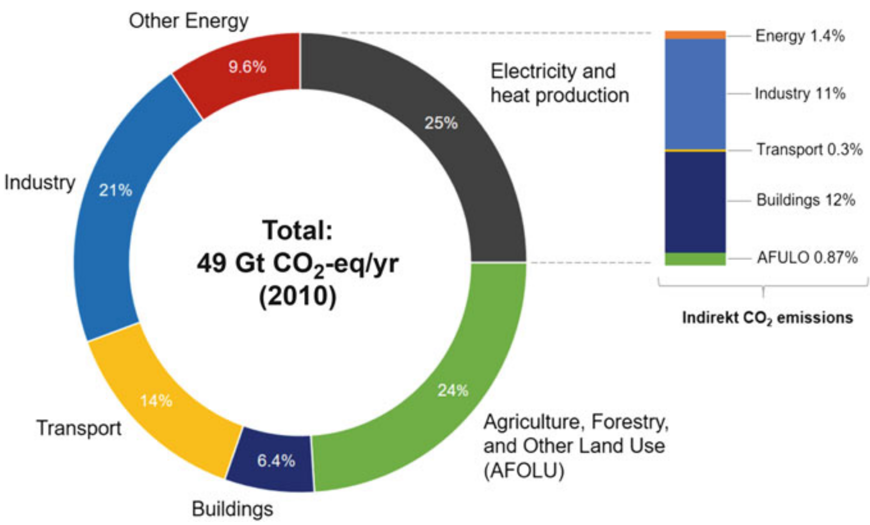

Fig. 2.2 Total anthropogenic greenhouse gas (GHG) emissions (gigatons of CO_2 equivalent per year, $GtCO_2$-eq/year) from economic sectors in 2010 (based on IPCC 2014)

(Fig. 2.2). CO_2 equivalents include the weighted effect of CO_2 ($GWP_{100\ year} = 1$), CH_4 ($GWP_{100\ year} = 28$) and N_2O ($GWP_{100\ year} = 265$) on global temperature. The higher the $GWP_{100\ year}$, the more a molecule of a GHG contributes to global warming and climate change (see Box 2.1) over 100 years.

Box 2.1 Climate Change
Greenhouse gases (GHG) in the atmosphere lead to the so-called greenhouse effect. The Earth's surface absorbs some of the energy from sunlight and heats up. It cools down again by giving off this energy in a different form, called infrared radiation. This infrared radiation escapes back to space, but, on the way, some of it is absorbed by GHG in the atmosphere, thus leading to a net warming of the Earth's surface and lower atmosphere (Fig. 2.3).

The direct and indirect effects of the increasing atmospheric concentration of GHG and concomitant increasing global temperatures are manifold and include (IPCC 2014):

- Ocean warming and acidification (through uptake of CO_2)
- Melting of the Greenland and Arctic ice sheets

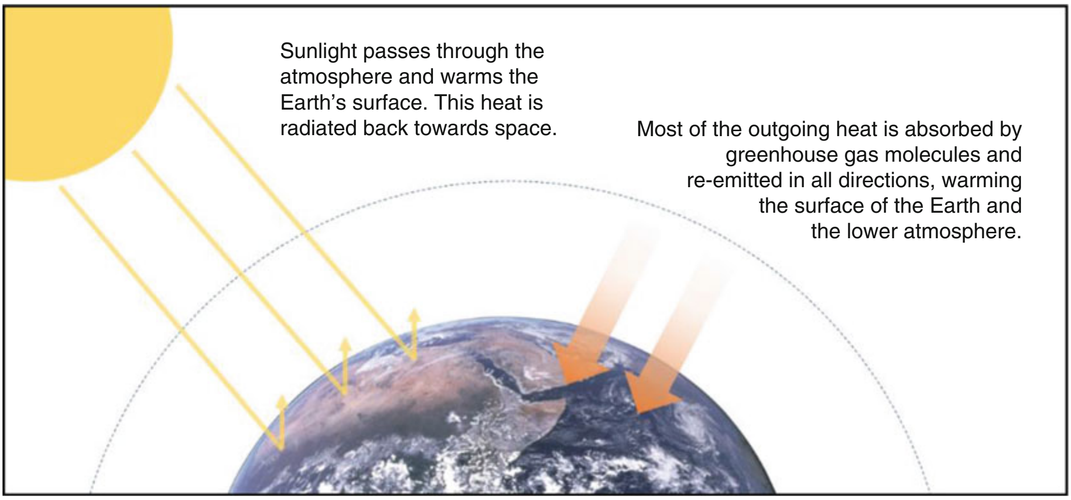

Fig. 2.3 How greenhouse gases lead to global warming (adapted from: http://climate.nasa.gov/causes/)

- Sea level rise (1.5–1.9 mm/year), threatening coastal communities and ecosystems
- Glacial retreat
- Decreased snow cover and increased permafrost temperatures
- Reduction in precipitation and increased occurrence of drought, especially in areas already critically affected by water limitation
- Extreme and unpredictable weather events such as storms and flooding
- Anticipated negative temperature, drought and other (e.g. diseases) impacts on agriculture, potentially leading to yield losses
- Negative impact on human health through deteriorating air and water quality, increasing the spread of certain diseases and altering the frequency or intensity of extreme weather events

The Intergovernmental Panel on Climate Change (IPCC) formulated a "climate goal" of 2 °C—the increase in global temperature that should not be exceeded in order to avoid disastrous global effects. To ensure CO_2-induced warming remains below 2 °C would require cumulative CO_2 emissions from all anthropogenic sources to remain below about 3650 $GtCO_2$ (1000 GtC); over half this amount had already been emitted by 2011 (IPCC 2014). One high potential GHG mitigation option is the use of biobased instead of fossil resources.

2.2 Biobased Resources

The resources produced and used in a biobased economy all contain carbon (C). Therefore, they can replace those fossil resources that contain carbon, i.e. coal, oil and natural gas.

In the following sections, biobased resources are defined as all resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams (see Sect. 5.1 for a more detailed description of biobased resources).

Biobased Resources
Biobased resources are of biological origin and stem from biomass. This biomass can be untreated or may have undergone physical, chemical or biological treatment.

Biomass
Biomass stems from living or once-living organisms including plants, trees, algae, marine organisms, microorganisms and animals.

Excluded are materials embedded in geological formations and/or fossilized.

Both biobased and fossil resources are derived from biomass that has been built through the process of photosynthesis (see Sect. 5.1). During that process, CO_2 is taken up by plants or algae with the help of light energy. Plants and algae convert light to chemical energy by integrating carbon (C) into their organisms. The carbon bound in fossil fuels was thus taken up from atmospheric CO_2 several million or billion years ago. By contrast, biobased resources are composed of recently grown biomass where there is a short time span of 1 to <100 years between the withdrawal of CO_2 from the atmosphere and its release back into the atmosphere. Therefore, biomass is often considered "CO_2 neutral" because the same amount of CO_2 is bound and then released again within a short period of time.

With an annual increment of 300,000 billion tons of biomass, biobased resources form a very large and, because they grow back, theoretically unlimited resource. However, their production necessitates the use of natural resources, mainly land, soil, water and plant nutrients.

2.3 Planetary Boundaries and Limitation of Natural Resources

Climate change is one of the nine planetary boundaries (Fig. 2.4) that the UN (Steffen et al. 2015) has characterized as demarcating the carrying capacity of the Earth and the vulnerability of global natural resources. According to these, climate change and land system change processes are already beyond the safe operating space. However, there are two categories that are at even higher risk. These are biosphere integrity (in particular genetic diversity) and biogeochemical flows (specifically nitrogen and phosphorus flows to the biosphere and oceans as a result of various industrial and agricultural processes) (see Box 2.2).

Box 2.2 Planetary Boundaries
"The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come" (http://www.stockholmresilience.org/research/planetary-boundaries.html):

1. Stratospheric ozone depletion
2. Loss of biosphere integrity (biodiversity loss and extinctions)
3. Chemical pollution and the release of novel entities
4. Climate change
5. Ocean acidification
6. Freshwater consumption and the global hydrological cycle
7. Land system change
8. Nitrogen and phosphorus flows to the biosphere and oceans
9. Atmospheric aerosol loading

(http://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html)

Integrity here refers to "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr and Dudley 1981, p. 56). It therefore has a functional as well as a quantitative (number of species and individuals) component (Angermeier and Karr 1994).

Agriculture—the primary source of food and feed and an important sector in the bioeconomy—has been responsible for

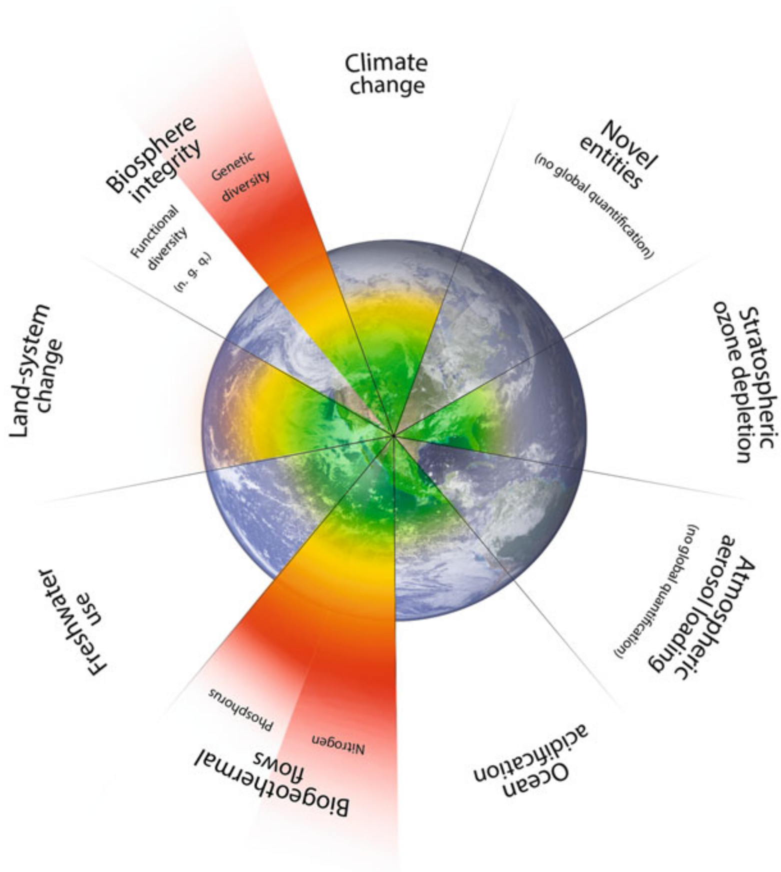

Fig. 2.4 The nine planetary boundaries. The *green-shaded* area represents the safe operating space

significant biodiversity losses. Key drivers of the decline in biodiversity and in conservation and ecosystem services are increased pesticide, herbicide and fertilizer use, increased landscape homogeneity associated with regional and farm-level specialization, drainage of waterlogged fields, loss of marginal and uncropped habitat patches and reduced fallow periods (Hilger et al. 2015; Lambin et al. 2001). The current high rates of ecosystem damage and extinction can be slowed by efforts to protect the integrity of living systems (the biosphere), enhancing habitat and improving connectivity between ecosystems while maintaining the high agricultural productivity that humanity requires (Steffen et al. 2015).

Other natural resources necessary for agricultural production are also under threat. While the production of agricultural goods increased 2.5–3 times over the last 50 years, the agricultural land area has only expanded by 12% (FAO 2011). Because more than 40% of the increase in food production stems from irrigated areas, water use has also increased. Today, 70% of all water withdrawn from aquifers, streams and lakes is used for agricultural production, leading to water scarcity in many areas of Asia, northern and southern Africa and western North America (FAO 2011). Intensive agricultural use and deforestation has also led to soil degradation processes, such as erosion. Very degraded soils are found especially in semiarid areas (sub-Saharan Africa, Chile), areas with high population pressure (China, Mexico, India) and regions undergoing deforestation (Indonesia) (UNEP 1997). Finally, the plant nutrient phosphorus (P) is also expected to become a limited natural resource for crop production. Phosphate fertilizer used in agriculture is mainly produced from rock phosphate (RP). However, RP is a finite resource, as with all mined resources. For this reason, in 2014, the EC added it to the list of critical raw materials (EC 2014).

Natural Resources
Natural resources occur naturally on the Earth. They include (a) biotic resources, stemming from living organisms (mainly plants and animals) and organic material (also fossil), and (b) abiotic resources from nonliving and inorganic material, such as air, soil, water, sunlight and minerals.

Because the bioeconomy makes direct use of natural resources—especially soil, land, water and nutrients—and therefore depends on their availability, it is at the focus of the sustainability debate. Only a bioeconomy that makes responsible use of natural resources, including their efficient use, conservation, restoration and recycling, can contribute to the transformation to a more sustainable economy. For this process, the bioeconomy will have to drive innovations further towards sustainable agricultural intensification. This is defined as "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" (Pretty et al. 2011). Sustainable agricultural intensification necessitates the use of innovative methods to produce modern varieties, fertilizers and crop protection measures. This aspiration is in line with recent trends, which show that about 70% of total factor productivity in agriculture is derived from innovations and only about 12% from land area extension. Also, other sectors producing biomass, such as forestry and aquaculture, need to apply sustainable production methods.

A sustainable bioeconomy cannot be achieved merely through replacing fossil resources by biobased resources to the maximal possible extent. It also requires that the replacement of fossil fuels by biobased resources results in an overall more sustainable economy.

2.4 Population Growth and Food Security

It is projected that the world's population will increase from the current seven billion people to nine billion by 2050 (FAO 2011, Fig. 2.5). Today (2017), almost one billion people are undernourished, particularly in sub-Saharan Africa (239 million) and Asia (578 million) (FAO 2011). In addition to the demands of the growing population, economic development, especially in the emerging economies, leads to increasing consumption of meat. That means the trend towards increasing meat consumption in the emerging economies of Africa and Asia, and the concomitant increase in global meat production (Fig. 2.6) will continue. It is estimated that by 2050 an extra billion tons of cereals and 200 million tons of livestock products will need to be produced annually (Bruinsma 2009). However, meat production requires more land than crop production. To produce 1 kg of meat, 3–100 kg of biomass is required, depending on which animals and production systems are used (Smeets et al. 2007). Therefore, future projections anticipate the need to increase food production by 70% globally and by 100% in the developing economies (FAO 2011).

In food production, quantity is not the only criterion; quality is also important. One of the first quality management steps in the biobased value chain is the protection of crop and animal health. This is aimed not only at delivering good quality foodstuffs but also at increasing productivity and reducing losses in the production, storage, transport and processing of biomass. Even before food discarded at consumer level is

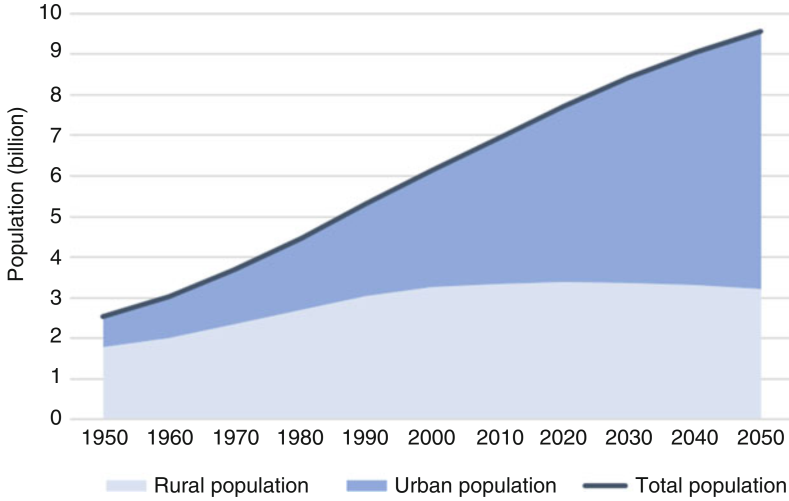

Fig. 2.5 World population trends for 1950–2050 (UNEP 2014)

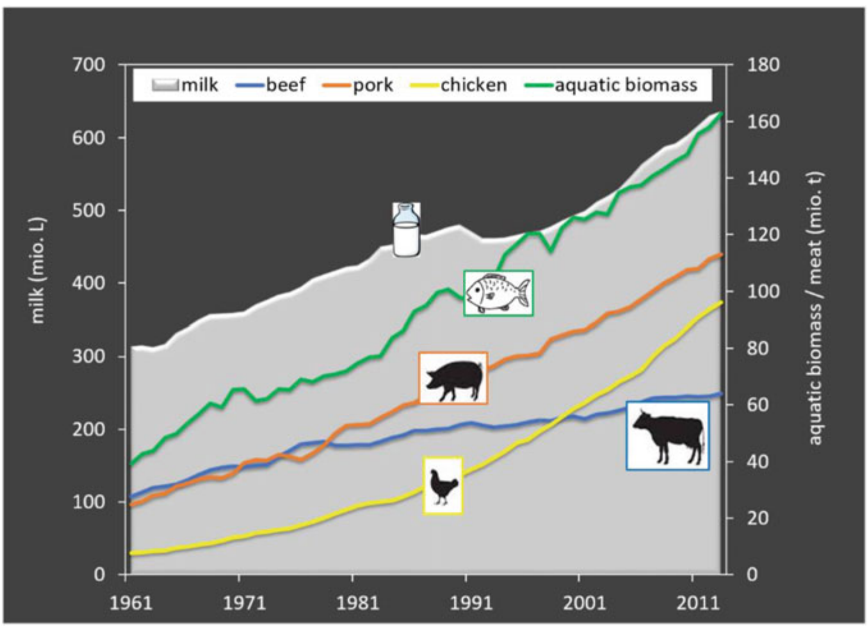

Fig. 2.6 Global meat, milk and fish (including crustaceans, molluscs and echinoderms) production for 1961–2011 (UNEP 2014; FAO 2015)

considered, food losses along the supply chain are estimated to be as high as 35% for cereals and more than 50% for perishable products such as roots, tubers, fruits and vegetables (Aulakh and Regmi 2013). Avoiding such losses requires disease-resistant varieties, effective crop protection measures and better training of farmers to apply these technologies, infrastructure for storage and transportation, and efficient processing and conversion methods.

The transition to a knowledge-based bioeconomy also depends on consumers being aware of the nature and characteristics of biobased products. Otherwise, they will neither be able to identify more sustainably produced products nor will they be willing to pay a higher price for higher-value goods. The process of raising awareness will also result in a more conscious choice of higher-quality, healthier products with a lower environmental impact and possibly in a reduction in meat consumption.

The availability of sufficient high-quality food for a growing population is thus not only a matter of sufficient production but also of appropriate use and food consumption patterns. The question of fair food distribution and adequate access of all people to food determines food security. In addition, today's hunger is not caused by insufficient global food production but by politically driven distribution problems.

2.5 The Role of the Bioeconomy in Dealing with Global Challenges

Bioeconomy is the sustainable and innovative use of biomass and biological knowledge to provide food, feed, industrial products, bioenergy, and ecological and other services. As such, it has the function of providing sufficient food of adequate quality and renewable resources to a growing population and at the same time making sustainable use of natural resources. The bioeconomy can help meet global challenges in the following ways:

- As non-renewable fossil resources are finite and have a high climate change impact, we need to meet our demands for food, products and energy through renewable resources. Foodstuffs and renewable materials can only be supplied by biomass from agricultural and forestry production as well as from aquaculture. Renewable energy on the other hand, to which bioenergy presently contributes 73% [biomass accounts for about 14% of global final energy consumption, REN21 (2016)], can also be supplied through solar, wind, geothermal, hydro or tidal energy.
- In a sustainable bioeconomy, the use of biobased resources should be optimized with regard to two main criteria. First, the demand for high-quality food for the world's population should be satisfied. Second, the remaining biobased resources should ideally be allocated with regard to the maximal ecological, social and economic benefit. This holistic approach in resource allocation is a major pillar of a sustainable bioeconomy and can serve as a blueprint for sustainable and general resource allocation strategies.
- Because land use presently contributes 24% of anthropogenic GHG emissions and a large part of biodiversity losses, agricultural and forestry land use management needs to be improved in a sustainable way. Climate-smart production methods need to be applied that make use of soil carbon sequestration and innovative technologies that reduce emissions and ecological impacts. These result in GHG mitigation and are often associated with improved efficiencies, lower costs and environmental co-benefits (Smith et al. 2007). In the bioeconomy, resource supply has to be sustainable, and therefore the use of biobased resources should only be implemented where these perform more sustainably than the fossil alternative.
- The global demand for more and higher-quality food and the limited availability of land and natural resources necessitate a thrust on innovation in agricultural, forestry, aquaculture and other forms of biomass production as well as biomass processing and use. This has to result in more efficient and less resource-consuming production methods along biobased value chains. Through a knowledge-based approach, more efficient and sustainable production methods must be applied in order to manage natural resources sustainably and increase productivity.
- The ubiquitous nature of biomass offers the possibility of creating modern jobs in rural areas, thus counteracting both the limited geographical distribution of accessible fossil resources and the current concentration of job and income opportunities in urban areas. The bioeconomy will enable areas poor in fossil but rich in biobased resources to improve income and development opportunities. The development of innovative technologies will

also generate new jobs with a modern profile (e.g. digitalization).

- The limited, and in part already overstretched, planetary boundaries render a shift to a more sustainable economy imperative, which makes better and responsible use of the Earth's resources. The change to a sustainable economy requires environmentally aware consumers, who steer economic activities through their targeted preferences and choices, and an overall sustainability-conscious behaviour of all stakeholders. Bioeconomy has become the guiding concept for large areas of economic development and societal transition so urgently needed to achieve this goal.
- The bioeconomy goes far beyond the idea of creating a biobased economy. It also builds on sustainable development through the application of biological and systems knowledge and the generation of innovations to develop a sustainable economy. This is not a sectoral approach in which only economic activities are considered that use biobased resources. Instead, the concepts of life cycle thinking and value chain approaches, resource use efficiency and recycling are applied to all production activities. Therefore, the bioeconomy is an integrated and forward-looking approach striving for an overall economic system optimization.

The bioeconomy can contribute to meeting global challenges through its nature as an economy building on renewable resources, biological knowledge, innovation and knowledge generation and through holistic approaches that think along value chains and in value nets. This means that the bioeconomy does more than just follow traditional pathways of biomass production, conversion and use. First, it must lead the way towards an innovative and sustainable use of the Earth's limited resources. Second, it has to provide guidelines for the societal transition towards sustainable development.

Review Questions

- What are the consequences, advantages and disadvantages of the use of fossil resources?
- How can the use of biobased resources overcome the shortcomings of fossil resources?
- How can the production of biobased resources help to keep the carrying capacity of the Earth within the planetary boundaries or, where they have already been exceeded, to fall back to within the boundaries?
- What are the potential contributions of the bioeconomy to meeting major global challenges?
- What conditions would be necessary for a sustainable bioeconomy?

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