Primary Production

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Iris Lewandowski, Melvin Lippe, Joaquin Castro Montoya, Uta Dickhöfer, Gerhard Langenberger, Johannes Pucher, Ursula Schließmann, Felix Derwenskus, Ulrike Schmid-Staiger, and Christian Lippert

Primary production is the synthesis of organic substances by autotrophic organisms from atmospheric or aqueous carbon dioxide (CO_2) (see Sect. 5.1). Primary productivity, which is the rate at which energy is converted into organic substances, depends on internal (genetic) and external (ecophysiological) factors. Figure 6.1 shows that the net primary production of biomass is highest in regions where high temperatures are combined with a good water supply and is totally absent in desert regions without a natural water supply.

Apart from light and water, there are other factors that determine primary productivity, including the availability of plant nutrients,

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Individual section's authors are indicated on the corresponding sections.

I. Lewandowski (✉)
Institute of Crop Sciences; Biobased Products and Energy Crops, University of Hohenheim, Stuttgart, Germany
e-mail: Iris_Lewandowski@uni-hohenheim.de

M. Lippe
Thünen Institute of International Forestry and Forest Economics, Hamburg, Germany
e-mail: Melvin.Lippe@thuenen.de

J. Castro Montoya • U. Dickhöfer
Institute of Agricultural Sciences in the Tropics; Animal Nutrition and Rangeland Management in the Tropics and Subtropics, University of Hohenheim, Stuttgart, Germany
e-mail: Joaquinmiguel.Castromontoya@uni-hohenheim.de; Uta.Dickhoefer@uni-hohenheim.de

G. Langenberger
Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute; Agronomy in the Tropics and Subtropics, University of Hohenheim, Stuttgart, Germany
e-mail: Gerhard.Langenberger@uni-hohenheim.de

J. Pucher
Department of Experimental Toxicology and ZEBET, German Federal Institute for Risk Assessment, Berlin, Germany
e-mail: Johannes.Pucher@bfr.bund.de

U. Schließmann • U. Schmid-Staiger
Department of Environmental Biotechnology and Bioprocess Engineering, Fraunhofer Institute for Interfacial Engineering and Biotechnology, Stuttgart, Germany
e-mail: ursula.schliessmann@igb.fraunhofer.de; schmid-staiger@igb.fraunhofer.de

F. Derwenskus
Institute of Interfacial Process Engineering and Plasma Technology, University of Stuttgart, Stuttgart, Germany
e-mail: felix.derwenskus@igb.fraunhofer.de

C. Lippert
Institute of Farm Management; Production Theory and Resource Economics, University of Hohenheim, Stuttgart, Germany
e-mail: Christian.Lippert@uni-hohenheim.de

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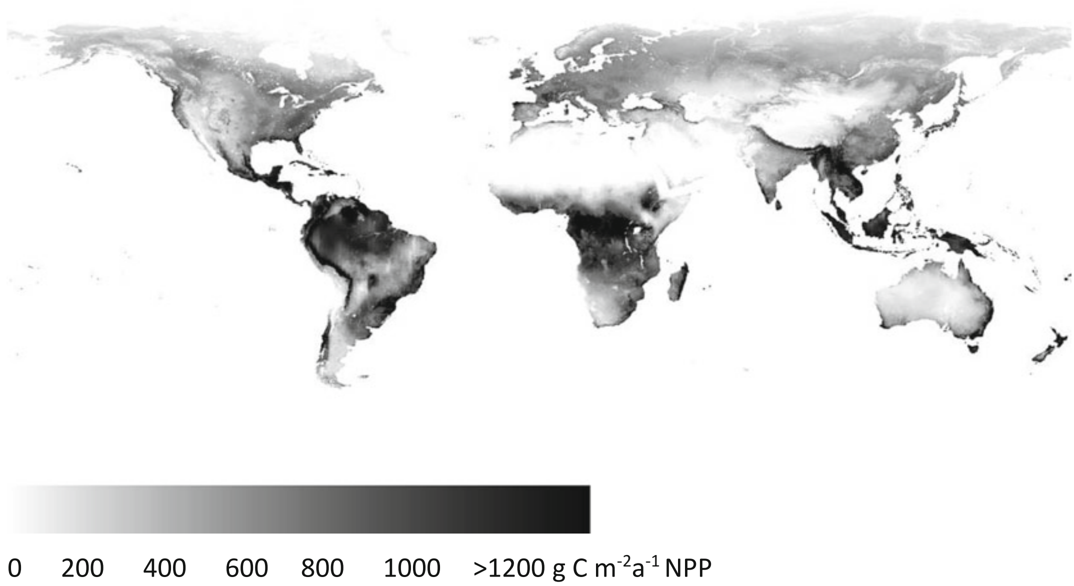

Fig. 6.1 Net primary production (NPP) of biomass, in gram increments of carbon (C) per m^2 and year (from Imhoff et al. 2004)

mainly nitrogen (N), potassium (K) and phosphorus (P) (Fig. 5.3). The lack of any one of these factors can hinder biomass growth. Unfavourable site conditions, such as soil contamination or compaction, can also impair biomass growth. Because the process of photosynthesis consumes CO_2, potential biomass productivity increases with increasing atmospheric CO_2 concentrations. However, this additional stimulus cannot be transformed into higher productivity if water supply is limited by drought. That means the highest biomass growth is achieved when all factors affecting growth are at their relative optimum.

Primary productivity also differs depending on the type of plant or organism and its genetics. An example of this can be seen in the productivity of ‘C3’ and ‘C4’ plants. Most crops cultivated in temperate climates possess the C3 photosynthetic mechanism, so called because the first product of carbon fixation contains three carbon atoms. Wheat, sugar beet and trees are examples of C3 crops. Carbon fixation in the photosynthesis pathway of C4 crops results in a first product containing four carbon atoms. Sugar cane and other subtropical and tropical crops belong to this group. Under favourable environmental conditions, especially high temperatures, C4 crops are more productive than C3 crops because they possess a more effective biochemical mechanism of fixing CO_2. The genetic component of productivity can be exemplified by the breeding progress achieved in recent decades. It is presumed that the major proportion of yield increases seen in the agricultural crops wheat, rice and maize are the result of intensive breeding. Improved crop management, especially fertilization and crop protection, is the second most important factor driving yield increases.

Actual biomass production very much depends on the kind of land use (see Fig. 6.2). The highest productivity is generally achieved on intensively managed cropland with natural vegetation generally having the lowest.

It is anticipated that a growing bioeconomy will require an increasing supply of biomass. However, not all of the biomass produced can

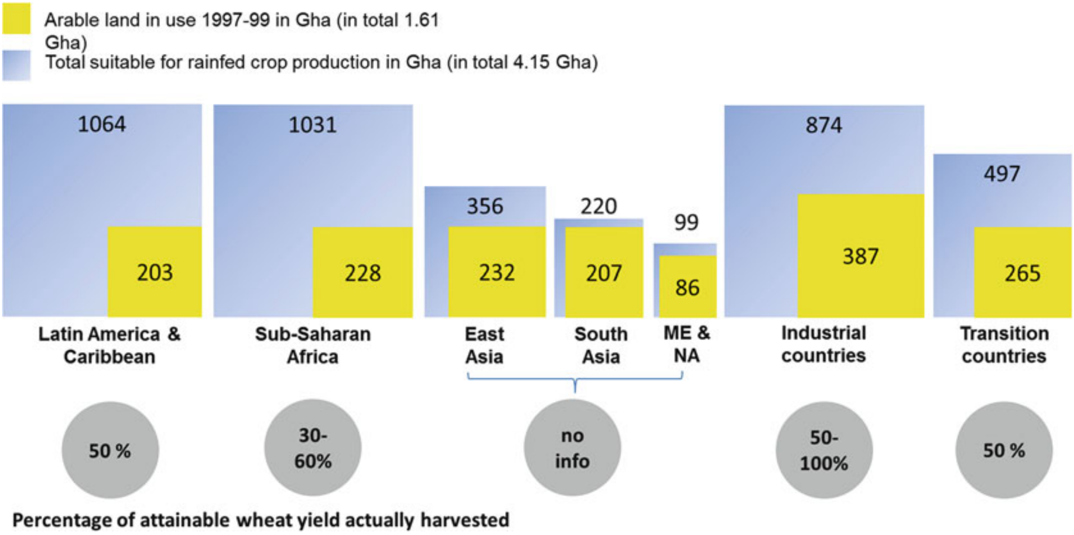

Fig. 6.2 Arable land in use and suitable for rainfed agriculture in different regions of the world. Also shown are the percentages of maximal attainable wheat yield in these regions (based on FAO 2002)

be made available for use. For example, in the context of bioenergy development, there is an ongoing debate about biomass availability and whether the energetic and material use of biomass is in conflict with food supply.

The question of how much biomass can be sustainably used for human consumption, especially for bioenergy, has led to various biomass potential analyses being performed. Several global biomass potential assessments indicate that an additional biomass potential exists for material or energetic application that could be used without jeopardizing food supply (Dornburg et al. 2010; Piotrowski et al. 2015; Smeets et al. 2007). The methods applied in these studies are generally supply-driven, which means they assess biomass potentials on the basis of resources available for biomass production. These resources are either additional land or land that can be more efficiently used to increase biomass productivity. Other supply-driven studies assess and quantify potential biomass supply from untapped or underutilized resources, such as agricultural and forestry residues, landscape and grassland biomass and other organic wastes.

Today, it is generally agreed upon that biomass potential assessment studies should follow the following rules (see also Dornburg et al. 2010):

- They should only consider biomass that is not required now or in future for the purpose of food production. A biomass potential should only be indicated as such if it can be generated in addition to products from primary production needed for food or feed purposes.
- Biomass should not be produced in any areas of high conservation value (HCV). The Roundtable on Sustainable Palm Oil (RSPO) defines HCVs as '. . . biological, ecological, social or cultural values which are considered outstandingly significant or critically important, at the national, regional or global level. All natural habitats possess inherent conservation values, including the presence of rare or endemic species, provision of ecosystem services, sacred sites, or resources harvested by local residents. An HCV is a biological, ecological, social or cultural value of outstanding significance or critical importance' (RSPO 2016).

Biomass should not be produced where it would lead to the destruction of high-carbon land-use systems, such as peat, natural forest or permanent grasslands.

- Biomass should be generated from the more efficient use of existing agricultural land and sustainable extraction from natural forests or other land-use forms. In addition, more efficient use should be made of existing biomass resources, for example, through more efficient biomass conversion techniques, and of residue streams to increase the biomass potential.

Recent studies have resulted in global biomass potentials ranging from 0 to more than 1100 GJ (Dornburg et al. 2010). The background assumptions applied in the modelling approach form the major determinant of the size of the biomass potential given. There are many factors that determine the sustainably usable biomass potential (Smeets et al. 2007; Dornburg et al. 2010) including:

- The local diet, mainly the kind and amount of meat and dairy products consumed. The biomass potential decreases with an increase in the amount of meat consumed because meat production requires 3–100 times more land than crop production (Smeets et al. 2007).
- The type and efficiency of meat production. The efficiency of meat production, expressed in terms of kg meat produced per kg feed, differs between animals, regions, feeding systems and others (see Sect. 6.1.10, Table 6.5).
- The efficiency of agricultural land use. The actual exploitation of agricultural land, indicated by the proportion of potential yield that is actually harvested, varies widely between countries. It can be close to full exploitation in industrial countries but as low as 30% in African countries (Fig. 6.2). Because biomass potentials are generally assessed by multiplying the respective yield by the amount of land available, the yield assumed is also a major determinant of biomass potentials.
- The amount and quality of land considered available for biomass production. The amount of land that is additionally available for biomass production is currently a topic of ongoing debate. The FAO (2002) estimated an untapped potential of 25 billion ha of agricultural land for rainfed biomass production (see also Fig. 6.2). However, large parts of these areas may be characterized as ‘marginal land’. Marginal production conditions can be defined in economic and biophysical terms (Dauber et al. 2012). Biophysical constraints to agricultural production include degradation though erosion, contamination, stoniness, and shallow soils and soils of low fertility. If marginal land is defined as land that does not support economically viable agricultural production, the status of marginality will depend on land-use and biomass prices. A caveat to the use of economically marginal land is the fact that the production of whatever biomasses, be it for food or energetic and material uses, on this land will result in low profit.
- The kind of biomass being considered. Lignocellulosic crops, such as trees and grasses, deliver the highest biomass and energy yields per hectare. Many potential studies (Hoogwijk et al. 2005; Smeets et al. 2007) are based on the assumption that short rotation coppice is grown on land available for biomass production. However, a number of material applications and liquid biofuel production require vegetable oils, sugar or starch. These can only be produced at lower yield levels.

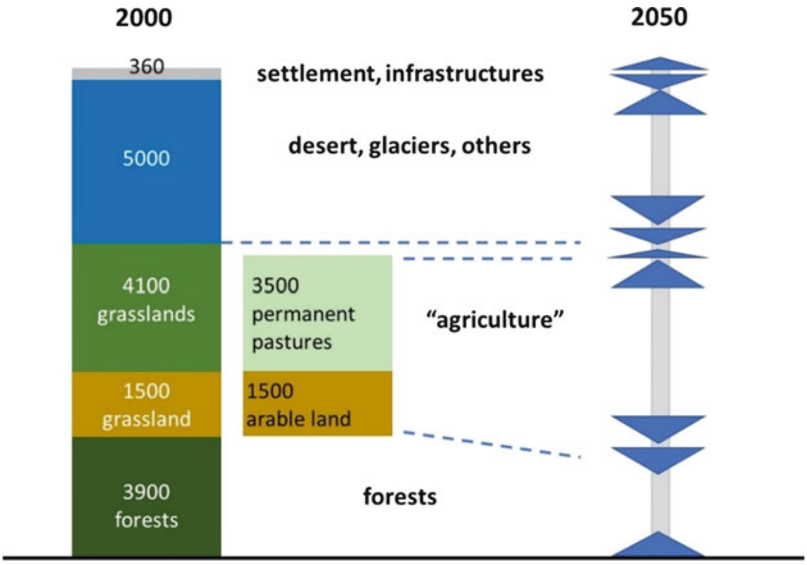

Fig. 6.3 Major types of global land-use cover in Mha and future trends (from UNEP 2014)

These bio-based resources are produced on a land area of 14,900 million ha (Mha) globally, of which 1500 Mha are arable land, 4100 Mha are permanent grassland and pastures and 3900 Mha are forest (Fig. 6.3).

Agriculture and forestry are the largest primary production sectors, followed by fishery, aquaculture and production of algae and microorganisms. Each of these primary sectors forms an important part of the bioeconomy. They are described in the following sections.

6.1 Agricultural Production

Iris Lewandowski, Melvin Lippe,
Joaquin Castro Montoya, and Uta Dickhöfer

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Abstract Agriculture is the cultivation of crops or the husbandry of livestock in pure or integrated crop/animal production systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. Together with forestry, agricultural production represents the main activity of resource production and supply in the bioeconomy and the major activity delivering food as well as starch, sugar and vegetable oil resources. Today, 33% (about 4900 Mha) of the Earth's land surface is used for agricultural production, providing a living for 2.5 billion people. Agriculture shapes cultural landscapes but, at the same time, is associated with degradation of land and water resources and deterioration of related ecosystem goods and services, is made responsible for biodiversity losses and accounts for 13.5% of global greenhouse gas emissions (IPCC 2006).

In the future bioeconomy, agriculture needs to be performed sustainably. 'Sustainable intensification' aims at shaping agricultural production in such a way that sufficient food and biomass can be produced for a growing population while, at the same time, maintaining ecosystem functions and biodiversity. Sustainable intensification can partly be achieved by the development and implementation of innovative production technologies, which allow a more efficient use of natural resources, including land and agricultural inputs. Its implementation requires a knowledge-based approach, in which farmers are made aware of the requirements of sustainable production and trained in the implementation of sustainable agricultural production systems.

The planning of bio-based value chains and sustainable bioeconomic development demands an understanding of the mechanisms of biomass production and supply (as described in this chapter) for the entire global agricultural sector.

Keywords Farming systems; Agricultural production systems; Crop production; Livestock production; Sustainable agriculture

Learning Objectives
After studying this chapter, you will:

- Have gained an overview of global agricultural production
- Be able to explain why different agricultural production systems are adopted in different regions
- Have become acquainted with the technological and logistical preconditions for agricultural production
- Understand the mechanisms of options for sustainable agriculture and intensification

Agriculture is the cultivation of crops and rearing of livestock in pure or integrated crop/livestock systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. Agricultural production systems are determined by the following factors: the production activity (crop, animal or integrated crop/animal production), the organizational form (e.g. small-scale family or large-scale industrial farm), the climatic (e.g. tropical, temperate) and other environmental conditions (e.g. soil properties) and socio-economic factors (e.g. population density, land availability, agrarian policy, farm and market structures). Agricultural production is performed by farming entities within an agroecosystem.

The terms ‘farm’ and ‘agroecosystem’ are defined below. This chapter describes how agricultural production systems are embedded in and determined by climatic, physical, environmental and societal conditions and the interactions (and interconnections) between them (Fig. 6.4). Furthermore, the principles of crop and animal production, their input and management requirements as well as their outputs, mainly in terms of yields, are described.

6.1.1 Farm Types

Farms are the entities that perform agricultural production by either cultivating crops or rearing livestock, or by a mixture of both. Farms are in general characterized according to size; available resources; local options for crop and animal production; organizational model and natural limitations of the surrounding agroecosystem, as a function of climate or soil types; and interaction with other floral and faunal species (Ruthenberg 1980; Seré and Steinfeld 1996; Dixon et al. 2001).

On a global scale, conservative approximations estimate that currently about 570 million farms exist, ranging from small-scale family farms to large-scale agro-industrial managed entities (Lowder et al. 2016). Family farms are still the most common farm type to date, where family members serve as the major work force. About 84% of all farms worldwide are classified as small-scale family or smallholder farms, cultivating on average about 0.5–2 ha of land, with 72% cultivating less than 1 ha and 12% cultivating about 1–2 ha only. These farms provide about 70–80% of agricultural products in Asia and Sub-Saharan Africa (IFAD 2013). Agro-industrial farming is characterized by larger-scale farming types based on production approaches known from industry, i.e. the use of mechanical-technical methods, large capital inputs and high productivity. These farms can be organized as family farms as well as by company-based organizational structures.

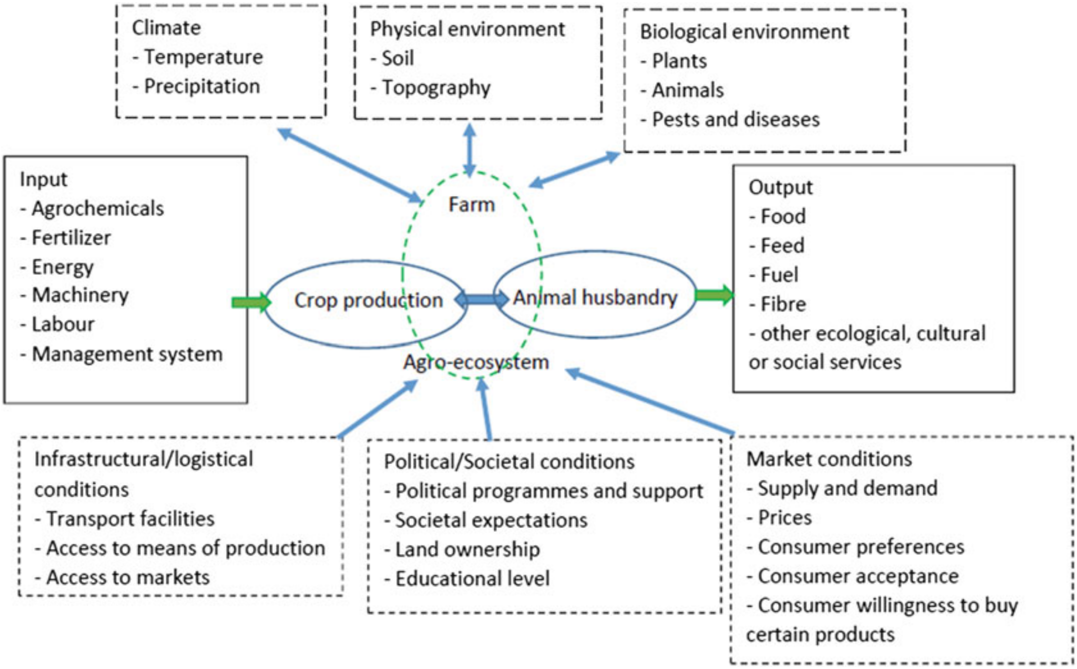

Fig. 6.4 Agricultural production systems and their determinants

Farming Systems

Farming systems can be classified according to the following criteria (Dixon et al. 2001):

- Available natural resource base, including water, land, grazing areas and forest
- Climate, of which altitude is one important determinant
- Landscape composition and topography
- Farm size, tenure and organizational form
- Dominant pattern of farm activities and household livelihoods, including field crops, livestock, trees, aquaculture, hunting and gathering, processing and off-farm activities
- Type of technologies used, determining the intensity of production and integration of crops, livestock and other activities
- Type of crop rotation: natural fallow, ley system, field system, system with perennial crops
- Type of water supply: irrigated or rainfed
- Level of annual and/or perennial crops used
- Cropping pattern: integrated, mixed or separated cropping and animal husbandry
- Degree of commercialization: subsistence, partly commercialized farming (if >50% of the value of produce is used for home consumption) and fully commercialized farming (if >50% of produce is used for sale)

Notably, fruit trees are often defined as perennial crops from an agricultural perspective and are not considered as forestry-based systems. However, exceptions are ‘agroforestry’ types that combine annual cropping with trees and pasture systems (referred to as ‘agrosilvopastoral’) or the combination of tree species and annual crops (referred to as ‘agrosilvicultural’).

Figure 6.5 provides an overview of the global distribution of the most important farming and land-use systems. Given the wide mixture of locally possible farm type systems, only broadly defined farm and land-use types are distinguished. Further information on regional farm-type composition can be found in the online databases and map portals listed at the end of this chapter.

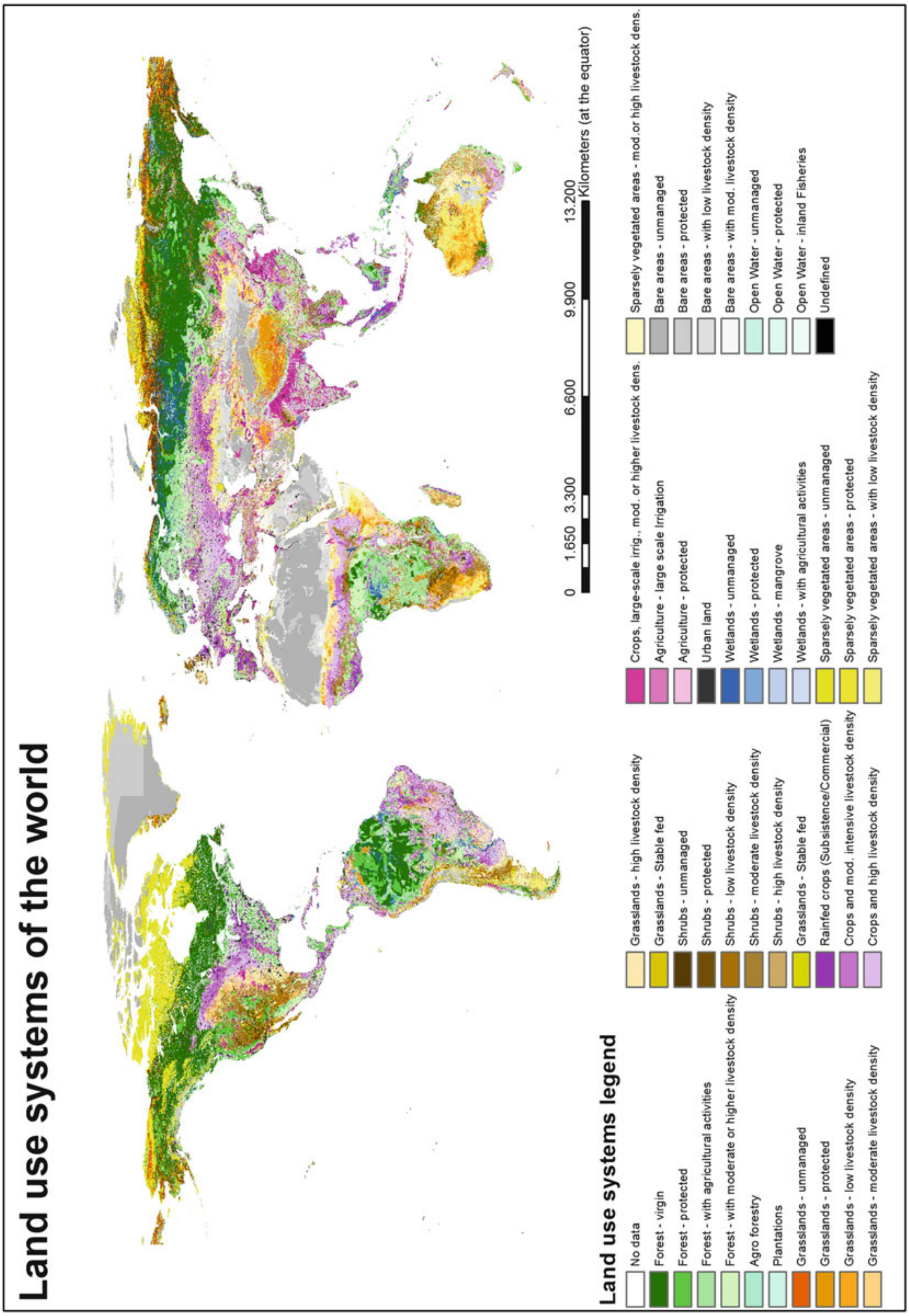

Fig. 6.5 Land use systems of the world (based on Nachtergaele and Petri 2008)

6.1.2 Agroecosystems

An agroecosystem can be defined as the spatial and functional unit of agricultural activities, including the living (=biotic) and nonliving components (=abiotic) involved in that unit as well as their interactions (Martin and Sauerborn 2013). It can also be described as the biological and ecophysiological environment in which agricultural production takes place. In this case, the environment consists of all factors affecting the living conditions of organisms. The different physical and chemical effects that originate from the nonliving environments represent the *abiotic factors*. In terrestrial habitats, they essentially include the properties of the soil (e.g. pH value, texture, carbon content), specific geographic factors (e.g. topography and altitude) and climatic conditions (e.g. precipitation, light and thermal energy, water balance). The effects of the *biotic* factors originate from the organisms and can be exerted on other individuals of the same species (intraspecific), on individuals of a different species (interspecific) or on the abiotic environment (e.g. on specific soil properties). From a species perspective, the biotic environment essentially consists of other species, to which it can have different forms of relationship. These include feeding relationships, competition and mutualism (Gliessman 2015; Martin and Sauerborn 2013).

6.1.3 Climate and Agricultural Production

As described above, the type of crops that can grow on a site mainly depends on the availability of water, the temperature and the light intensity. Agricultural production can therefore be characterized according to the climatic zone, classified according to temperate, subtropical, or tropical conditions. Deserts also sustain some extensive agricultural use through grazing. Climatic zones can also be distinguished according to the original vegetation, e.g. forests. Table 6.1 gives an overview of the main climatic/vegetation zones, their characterization and selected major food and energy crops cultivated.

6.1.4 Physical Environment and Agricultural Production

The physical environment mainly determines options for agricultural production through the topography of the landscape and soil properties.

The topography defines if or how well the land can be accessed and managed mechanically. Soil cultivation, such as ploughing, is difficult on steep slopes, and there is the danger of erosion.

The soil characteristics most relevant for crop production are:

- Organic matter, mainly occurring in the upper A soil horizon (see Fig. 6.6). Organic matter determines the soil's water-holding capacity and can supply plant nutrients.
- Soil texture or grain size distribution (clay: <0.002 mm; silt: 0.002–0.05 mm; sand: 0.05–2 mm), which determines the water-holding capacity and workability of the soil as well as its susceptibility to degradation processes.
- The pH, which is a numeric scale used to specify the acidity ($pH < 7$) or basicity ($pH > 7$) of the soil.
- Soil depth, bulk density and stoniness. These determine the water-holding capacity of the soil, how well it can be treated mechanically, how well plant roots can penetrate it and how much space is available to plant roots for the acquisition of water and nutrients.

Crop production requires the natural resource soil. However, it is directly or indirectly responsible for the largest part of soil degradation processes, such as erosion and compaction. Soil degradation occurs when (a) forests are cleared to make room for agriculture, (b) conversion of land to intensive soil cultivation subjects the organic matter and upper horizons of soil to

Table 6.1 Major agricultural production systems in different climatic regions of the world (based on Davis et al. 2014)

Biome and type of agriculture	Rainfall mm a^{-1}	Temp. °C[a]	Growing days[b]	Potential crops[c]
Subtropical/temperate humid forest Large commercial and smallholder: intensive mixed agriculture, cereals and livestock, tree crops	1000–2500	10–30	270–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, sugar crops, fruit, vegetables
Temperate broad-leaved forest Large commercial and smallholder: tree crops, forest-based livestock, large-scale cereal and vegetables, cereal/livestock	250–1500	−10–30	90–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, fruit, vegetables
Temperate coniferous forest Forestry, large commercial and smallholder: cereals/roots, forest-based livestock	100–1500	−30–5	30–180	Cereals[d], roots, tubers
Temperate grassland Large commercial and smallholder: irrigated mixed agriculture, small-scale cereal/livestock, livestock	50–1000	−10–30	0–320	Cereals[d], fibres, oil crops, roots/tubers, sugar crops, fruit, vegetables
Tropical dry forest Large commercial and smallholder: tree crops, rice, cereals/roots	700–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical grassland Large commercial and smallholder: extensive, commercial ranching or mobile pastoralist systems, livestock	500–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical humid rainforest Large commercial and smallholder: subsistence agriculture, livestock, tree crop, root crop, partly protected land	1500–5000	25–30	300–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, tea, coffee, sugar crops, fruit, vegetables
Temperate and tropical desert Pastoralism	0–350	10–40	0–30	Succulents

[a] Average annual temperature, based on FAO GeoNetwork (2017a, b)

[b] In general, growth is limited by rainfall (or water availability) in tropical climates and by temperature in temperate climates; species might have evolved locally in order to survive the extremes of climate, some crops may not, leading to zero growing days. Crop selection and management can potentially extend the growing season in other cases

[c] Within a biome, the suitability of a site for a particular crop depends on a range of factors, including altitude, aspect, rainfall and soil type. Crops listed here are examples and are not intended to be a comprehensive list

[d] Cereals crops are generally of the gramineous family and are cultivated to harvest dry grain only (as food or feed) or the total plants (as feed or bioenergy source), e.g. wheat, rice, barley, maize, rye, oat, millet, sorghum, buckwheat, quinoa, fonio, triticale and canary seed

decomposition and runoff and (c) inappropriate soil cultivation methods lead to compaction and erosion.

Degradation of agricultural soils can be prevented or even reversed by appropriate management methods, but in some cases it requires time spans of decades or centuries for full restoration. Conservation and low-tillage farming, where the tilling of soil is kept to a minimum or avoided altogether, strive to preserve soil fertility. There are a range of measures through which the farmer can maintain soil fertility, including (a) maximizing soil coverage by intercropping, crop rotation optimization and mulching, (b) enhancing soil organic matter supply through intercropping and applying crop residues; (c) reducing soil

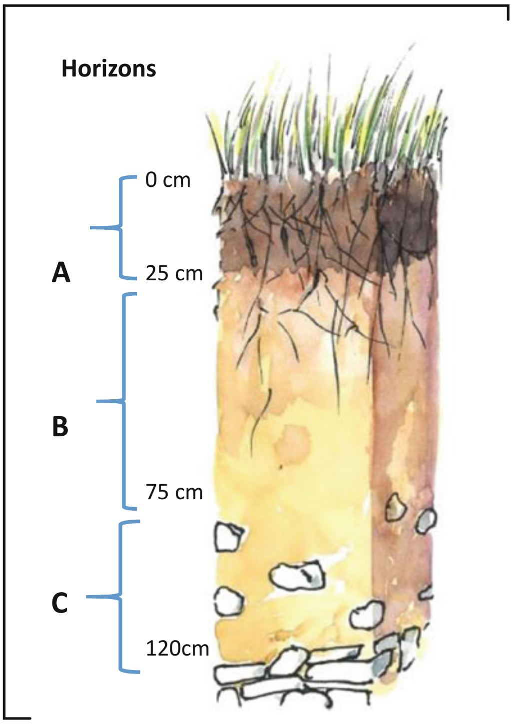

Fig. 6.6 Typical soil profile with different horizons © Ulrich Schmidt

cultivation intensity and growing perennial crops and (d) avoiding erosion by contour farming, i.e. soil cultivation parallel to slopes.

Soil Erosion

Soil erosion is the physical loss of soil caused by water and wind. Rainfall leads to surface runoff, especially when soil has been cultivated, is not covered by vegetation or is on a steep slope. Wind erosion mainly occurs in semiarid and arid regions. In this process, wind picks up solid particles and carries them away. Erosion is a major process in soil degradation.

6.1.5 Biological Environment and Agricultural Production

The biological environment (=biotic factors) refers to the natural occurrence of organisms, such as animals, plants, microorganisms, bacteria and viruses, at a specific site. These can all become constraints in crop production and livestock husbandry, for example, through animals eating the crops; weeds competing with crops for nutrients and water; crops becoming infected with fungal, viral or bacterial diseases; or the competition for and lack of fodder of moderate-to-high quality for animal feeding.

At the same time, agricultural production has a strong impact on biodiversity through the use of pesticides, herbicides and fertilizers, increased landscape homogeneity associated with regional and farm-level specialization and habitat losses when natural vegetation is converted to agricultural land (Hilger and Lewandowski 2015; Lambin et al. 2001).

Mixed cropping systems may lead to higher overall product yields than monocultures. However, if the target is the maximization of the yield of one specific crop, the highest area yield is achieved by monoculture, i.e. the cultivation of a single crop or variety in a field at a time. This is because the management system (i.e. crop protection, fertilization, harvesting time) can be best optimized for a homogenous plant community. Any other plants in the field compete with the crop for growth-promoting factors (water, light and nutrients) and are therefore considered weeds that need to be controlled or eradicated in order to avoid a reduction in crop yield. Animals that feed on the crops are also in conflict with agricultural production, except for natural predators of pests (e.g. birds of prey that catch mice) and beneficial insects (e.g. ladybirds than eat aphids), which help to increase agricultural crop productivity.

There are two concepts which are often discussed in the context of agriculture and maintenance of biodiversity: land sharing and sparing. ‘Sharing’ refers to the attempt to integrate as much biodiversity as possible into the agricultural area, generally at the expense of productivity. ‘Sparing’ aims to divide the land into areas used intensively for agriculture and others left natural and uncultivated. There is scientific evidence that the principle of sparing may be more successful in supporting biodiversity than that of sharing.

6.1.6 Infrastructure and Logistics

Mechanization has greatly enhanced land-use and labour productivity. In modern agricultural production, all processes of soil cultivation, crop establishment, fertilization, crop protection and harvesting are performed mechanically by agricultural machinery specifically optimized for the crop at hand. For this reason, modern agriculture is capital-intensive. In order to secure a reliable and efficient supply chain with low losses, infrastructure and logistics are required for the agricultural production system and storage and transport of the products to the markets. The better the infrastructure and logistic conditions, the lower the supply chain losses. These can reach up to 70% in areas where agricultural infrastructure is poorly developed. The lack of infrastructure (roads, storage facilities) is seen as a major barrier to increasing biomass supply in developing countries. Huge investments would be required to overcome these bottlenecks.

Digitalization is becoming increasingly relevant in contemporary agricultural infrastructure. Modern tractors are equipped with electronic devices, such as GPS (Global Positioning System). In precision farming (see Box 6.4), for example, GPS, electronic sensors and computer programs steer the spatially specific and resource-use-efficient application of agrochemicals.

6.1.7 Political and Societal Conditions

Agricultural, environmental and market policies have a significant impact on agricultural production in terms of what is produced and how. Examples of market policy impacts are described in Sect. 8.1. Agricultural policy programmes are made by many nations, and so-called common agricultural policies (CAP) determine agricultural policies at EU level. They mainly steer the subsidies provided to farmers and the production volumes of certain agricultural commodities. In the 1990s, European agriculture produced more than the markets could take up without detrimental price effects. Therefore, farmers were obliged to set land aside and and compensated. At that time, 15% of land had to be set aside. Today this land is required for the production of energy and industrial crops, and no more set aside obligations exist. Currently CAP rules determine how agricultural subsidies are coupled to environmental beneficial management measures under the so-called ‘cross-compliance (CC)’, and farmers are obliged to integrate ‘greening areas’ to support biodiversity.

Societal expectations determine how agricultural and environmental policy programmes are framed. For example, in Europe there is little acceptance of genetically modified organisms (GMO; see Sect. 5.1), and the production of GM crops is strictly forbidden.

As has been described above (Sect. 6.1.1), the evolution of farming systems very much depends on social structures, especially how land access is granted and who owns how much land. Also, the educational level of farmers not only determines the success or income of farms, but also whether farmers have the knowledge and willingness to manage their farm sustainably. Finally, the empowerment of farmers is an important condition for shaping a sustainable agriculture for the future.

6.1.8 Market Conditions

The most important animal-based products globally are cow milk and cattle, pig and chicken meat (see Table 6.2). Rice, wheat and maize are the most important crop-based commodities and are traded globally. Section 8.1 describes how supply and demand steer the agricultural commodity markets and determine market prices.

There are local, regional and global markets. But it is the demand of those markets that are accessible to farmers that determines what and how much they produce.

Consumer preferences and the consumer’s willingness to buy certain products and to pay a certain price are important market determinants.

Table 6.2 Top agricultural products in terms of production value and production quantities, world 2012 (FAOSTAT 2014)

Commodity	Production in $1000	Production in MT
Milk, whole fresh cow	187,277,186	625,753,801
Rice, paddy	185,579,591	738,187,642
Meat, indigenous, cattle	169,476,916	62,737,255
Meat, indigenous, pig	166,801,086	108,506,790
Meat, indigenous, chicken	132,085,858	92,730,419
Wheat	79,285,036	671,496,872
Soybeans	60,692,327	241,142,197
Tomatoes	59,108,521	161,793,834
Sugar cane	57,858,551	1,842,266,284
Eggs, hen, in shell	54,987,685	66,372,549
Maize	53,604,464	872,791,597
Potatoes	48,770,419	365,365,367

The willingness of consumers to pay a certain price is especially important for sustainably or ‘better’-produced products. One of the challenges in a bioeconomy is that ecologically more sound production is accompanied by higher production costs. Therefore, bio-based or sustainably produced products are often more expensive than conventional ones. Markets for bio-based products can only develop if consumers are well informed and willing to make a conscious choice for the ‘better’ product.

6.1.9 Principles of Crop Production

Every crop performs best in specific climatic conditions and can best be grown in either a temperate, subtropical or tropical climate (see also Table 6.1). The climatic profile of a crop is usually determined by the region of its origin (see Fig. 6.7 and also: http://blog.ciat.cgiar.org/origin-of-crops/). Breeding (see Sect. 5.1.2) can produce crop varieties that are adapted to specific climatic conditions. A prominent example is maize, whose cultivation area in Europe was extended north by breeding for cold tolerance.

The most important prerequisite for successful crop production is the choice of an appropriate crop and variety for a specific site. This does not only refer to climatic parameters. Crops also have specific demands with regard to soil conditions and biotic (e.g. pests and diseases) and abiotic (e.g. drought, contamination, salinity) stresses. In addition, the appropriate management measures need to be chosen according to the crop and site conditions (see Fig. 6.8). Whereas site conditions are given naturally, crop management is the anthropogenic influence on crop production.

Crop rotation is the temporal sequence of crops on a field. If annual crops (seeding and harvesting in the course of 1 year) are grown, the farmer can choose a new crop every year. Perennial crops are grown on the same field for 3–25 years, depending on the optimal production period of the crop. Intercropping is the integration of a catch crop in between two major crops. Catch crops are often grown to prevent soil runoff (erosion) or nutrient leaching or to provide organic matter to the soil. Crop rotations are generally optimized from an economic viewpoint, i.e. those crops with the highest market value are grown. However, there are biological and physical limits to crop rotation planning. It has to allow enough time for field preparation between the harvesting of one crop and the sowing of the next. Generally, it is not recommended to cultivate the same crop in a field for two or more consecutive years because pests, diseases and weeds often remain in crop residues and soils and can attack the follow-on crop. A change of crop is also necessary due to the depletion of soil nutrients. For this reason, it is recommended to avoid growing the same crop, or crops with similar demands and susceptibility to pests and diseases, in succession.

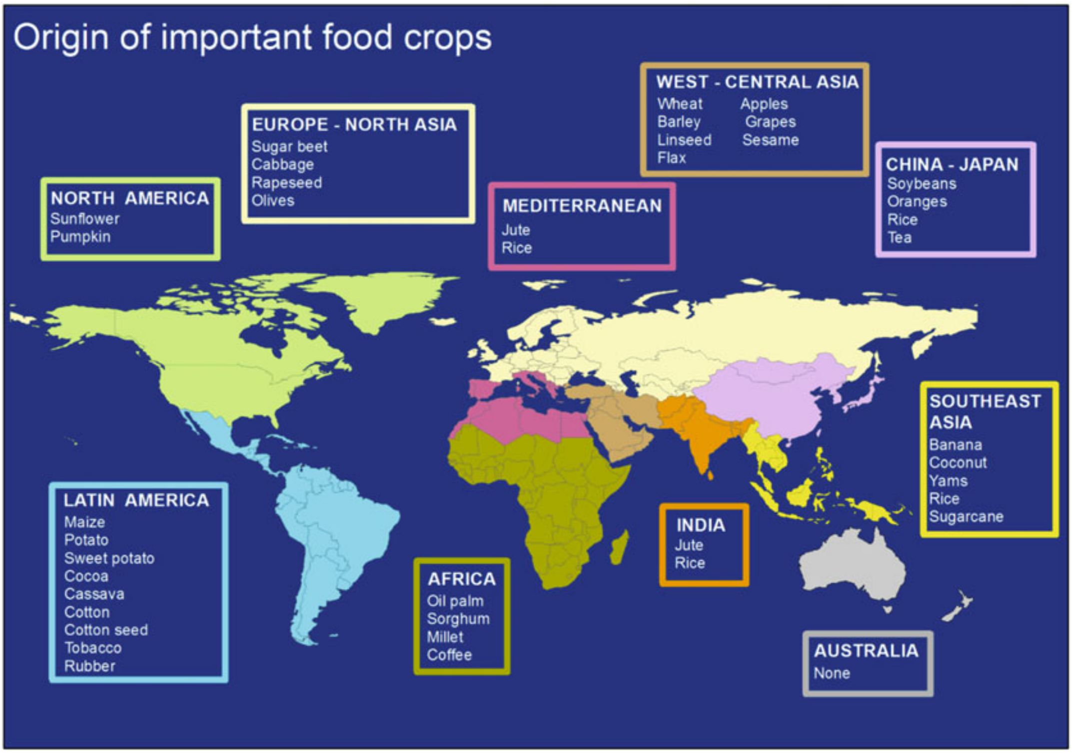

Fig. 6.7 Origin of important food crops (based on Khoury et al. 2016)

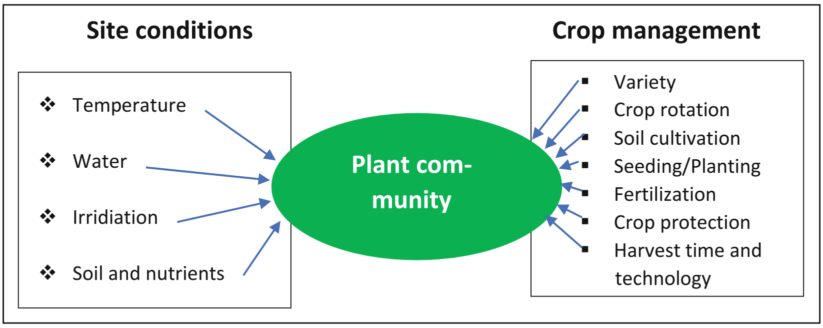

Fig. 6.8 Factors determining success of crop production

Soil cultivation is performed to loosen the soil, to incorporate residues, organic and mineral fertilizer, to control weeds and to prepare the soil for sowing or planting. The timing of and technology used for soil cultivation have to be adapted to the demands of the crop and soil conditions. Treating a wet soil and using heavy machinery can have negative impacts on the soil structure (compaction). Ploughing is the most effective soil treatment in terms of soil loosening and weed control. However, to protect soil organic matter and to avoid erosion, less intensive soil cultivation technologies are to be preferred. These, however, can lead to increased weed pressure and weed control demand.

Crops are established via *sowing* or *planting*. Sowing is cheaper and easier to mechanize and is the method used for most major crops, such as

Table 6.3 List of selected crops with information on water, fertilizer and pesticide demand, parts harvested and constituents utilized

	Sugar cane	Corn	Soy	Oil palm	*Miscanthus*
Crop type	Perennial	Annual	Annual	Perennial	Perennial
Photosynthetic pathway	C_4	C_4	C_3	C_3	C_4
Water demand (mm a^{-1})	High: 1500–2500	Moderate: 670–800	Moderate: 600	High: 2000–2500	Low: >450
Fertilizer demand (kg ha^{-1} a^{-1})	N: 45–300 P: 15–50 K: on demand	N: 145–200 P: 26–110 K: 25–130	N: 0–70 P: 32–155 K: 30–320	N: 114 P: 14 K 159	N: 0–92 P: 0–13 K: 0–202
Pesticide needed?	Yes	Yes	Yes	Yes	No
Main parts harvested	Stems, leaves	Grain	Grain	Grain	Stems
Constituents utilized	Sugar	Starch	Oil	Oil	Lignocellulose
Uses	Food, biochemicals/ fuels, (feed)	Food, feed, biochemicals/ fuel	Feed, biodiesel	Food, biochemicals a.o.[a]	Bioenergy, building materials, biocomposites, second-generation biochemicals

[a] Oil derivatives are used in the cosmetic and other industries (from Davis et al. 2014)

cereals, maize, sugar, oilseed rape, etc. Some crops have to be planted. Examples are sugar cane, which is established via stem cuttings, and oil palm, established via plantlets. In each case, the soil has to be prepared for planting by loosening it and removing weeds that would hamper crop establishment (soil cultivation).

Fertilization refers to all measures aimed at supplying nutrients to the crop (e.g. application of mineral or organic fertilizer) or improving soil conditions relevant for nutrient uptake (e.g. liming or application of organic substances). The optimal amount of fertilizer is determined according to the expected nutrient demand and withdrawal by the crop. Nitrogen (N) is the nutrient with the strongest yield effect. It is supplied to the soil via mineral or organic fertilizer, N-fixing legumes or atmospheric deposition. In ecological agriculture, N is only supplied via organic fertilizer and biological N fixation (see Box 6.1). In addition, potassium (K), phosphorus (P) and calcium (Ca) are required for optimal crop growth and are generally applied when in shortage. As well as being a plant nutrient, Ca has an influence on soil structure and pH. The so-called crop macronutrients also include magnesium and sulphur (S). These are often combined with PK fertilizer and are only applied when there is an obvious shortage. This also applies to the so-called micronutrients, such as iron (Fe), chloride (Cl), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), cobalt (Co) and nickel (Ni), which are only required in small quantities. Typical fertilizer requirements of major crops, including biomass crops, of temperate regions are shown in Table 6.3.

Crop protection refers to measures for the suppression or control of weeds, diseases and pests. Weeds compete with crops for all factors affecting growth and reduce crop yield and/or quality. So do pests and diseases, which feed on plant parts or their products of photosynthesis and often reduce the photosynthetically active surface area of plants. Every crop has a range of pests and diseases to which it is susceptible. Diseases can be caused by fungi, bacteria or viruses. If weeds, pests and diseases are not controlled, they can lead to large or total crop losses. There are a number of crop protection measures including mechanical (e.g. weeding) and chemical (herbicides, pesticides (Box 6.2)) methods. In organic agriculture (Box 6.4), no chemical/synthetic crop protection measures are allowed. Instead, biological methods (e.g. natural predators, pheromone traps) are used together with biological pesticides (e.g. extracts from neem tree) and mechanical weed control.

Harvest technology and timing are relevant for the harvest index (proportion of harvested product versus residues) and the quality of the product. Appropriate harvest time and technology avoid pre- and postharvest losses.

Box 6.1: Biological Nitrogen Fixation

Nitrogen (N) is one of the most abundant elements on Earth and occurs predominately in the form of nitrogen gas (N_2) in the atmosphere. There is a specialized group of prokaryotes that can perform biological nitrogen fixation (BNF) using the enzyme nitrogenase to catalyse the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3). Plants can readily use NH_3 as a source of N. These prokaryotes include aquatic organisms (such as cyanobacteria), free-living soil bacteria (such as *Azotobacter*), bacteria that form associative relationships with plants (such as *Azospirillum*) and, most importantly, bacteria (such as Rhizobium and *Bradyrhizobium*) that form symbioses with legumes and other plants (Postgate 1982).

In organic agriculture, BNF is the major N source, and leguminous crops are grown for this purpose. There have been many attempts to associate N-fixing bacteria with crops other than legumes, with the objective of making them independent of external N supply. It is anticipated that BFN will play a major role in the sustainable intensification of agricultural production.

Box 6.2: Pesticides

Pesticide means any substance, or mixture of substances of chemical or biological ingredients, intended for repelling, destroying or controlling any pest or regulating plant growth (FAO and WHO 2014).

Pesticides can have different chemical structures (organic, inorganic, synthetic, biological) and target organisms.

Crop Yields

Crop yields depend on the climatic and management factors depicted in Fig. 6.9. Thus, yield potentials have a climatic/site-specific and a management component. They usually increase with the educational level of farmers and their access to means of production, in particular fertilizer and pesticides. The potential yield on a specific site, which is mainly determined by crop genetics and growth-promoting factors, is generally much higher than the achievable yield (Fig. 6.9). The achievable yield is limited by the availability of nutrients and water and can be improved by yield-increasing measures, such as fertilization and irrigation. The actually harvested yield, however, is normally lower than the achievable yield, because it is reduced by pests and diseases and/or harvest losses. These can partly be overcome through improved crop management and agricultural technology, such as efficient harvesting technology.

The ratio of actual to achievable yield is highest in industrial and lowest in developing countries where farmers have less access to means of agricultural production and are less educated (see Fig. 6.2). For this reason, and also due to climatic differences, it is not possible to provide yield figures for the performance of a crop on every site and for all circumstances. Table 6.4 provides typical, average yields for selected major crops per hectare (ha $= 10{,}000\ m^2$).

6.1.10 Principles of Livestock Production

Global Livestock Population Trends

Global livestock production has a value of at least US$1.4 trillion and employs about 1.3 billion people (Thornton 2010). Livestock has a great significance in the livelihoods of people in the developing world, providing support for 600 million poor smallholder farmers (Thornton 2010).

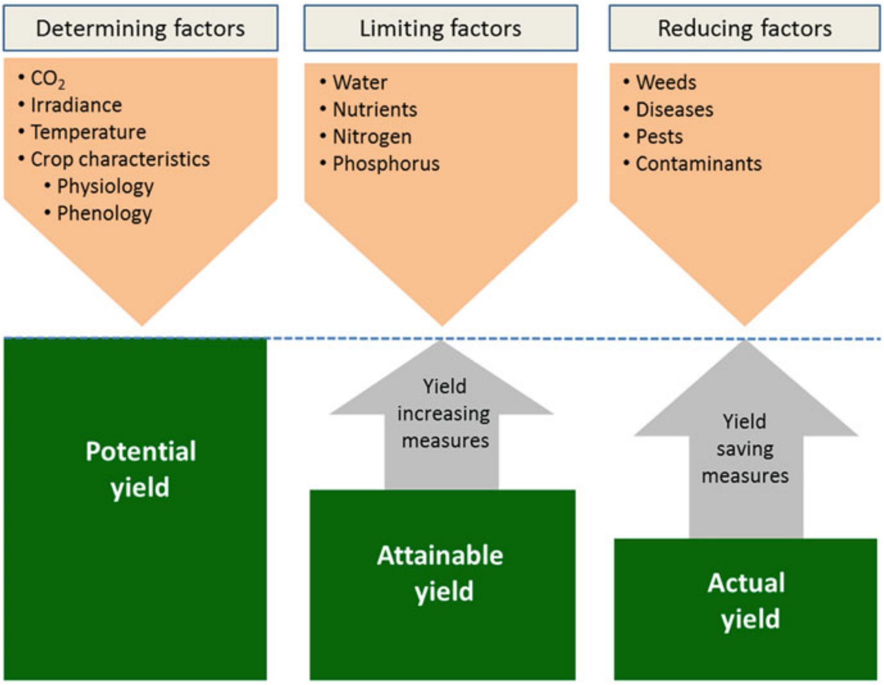

Fig. 6.9 Determination of crop yields (adapted from Rabbinge 1993)

Between 1961 and 2014, the number of animals in the least-developed countries (LDC) increased 2.4-, 7.1- and 6.9-fold for cattle, chicken and pigs, respectively, with major increases in the last two decades. By contrast, in the European Union (EU), livestock populations increased about 1.5-fold between 1961 and the beginning of the 1980s and, since then, have remained more or less stagnant with slight decreases in cattle and slight increases in chicken populations (author's own calculations; FAOSTAT 2017).

Primary production from livestock has increased in both developing and industrialized countries. In developing regions, this is a result of increasing livestock populations and performance levels (e.g. kg milk or meat/animal), whereas in industrialized countries the growth has almost exclusively been achieved by improving animal performance. There is still a large yield gap between industrialized and developing countries. In 1961, yields of chicken and pig meat per animal were 52% and 92% higher, respectively, in the EU than in the LDC. In 2014, these yields were still 40% and 49% higher, respectively, in the EU than in the LDC. For cattle, the productivity gap between industrialized and developing countries has even increased in the last 50 years. In 1961, milk yields were 9.8-fold higher and meat yields 1.5-fold higher in the EU than in the LDC. In 2014, they were 20- and 2.3-fold higher, respectively (author's own calculations; FAOSTAT 2017).

Classification of Livestock Production Systems Livestock production systems vary greatly between different regions of the world, and their development is determined by a combination of socio-economic and environmental factors. Many of these systems are thus the result of a long evolution process and have traditionally been in sustainable equilibrium with their surrounding environments (Steinfeld et al. 2006). Livestock production systems are generally classified based on the following criteria (Seré and Steinfeld 1996; Steinfeld et al. 2006):

- Integration with crops
- Relation to land

Table 6.4 Average yields of selected crops (in dry matter DM) (from KTBL 2015; FNR 2008; FAOSTAT 2014)

Crop	Harvested product (main ingredient)	Yields (t DM ha^{-1} a^{-1}) of harvested products			Typical uses	Major producing country
		Low	Average	High		
Temperate						
Wheat	Grain (starch)				Food, feed, biofuel	Europe, Ukraine, USA
Summer		3.4	5.4	7.1		
Winter		5.4	7.4	9.5		
Corn/maize	Grain (starch)	6.2	9.5	12	Food, feed, biofuel	USA, Europe
	Whole crop	12	18	25	Feed, biogas	
Potato					Food, feed, biofuel, bioplastics	Europe
Rape seed	Seed (Oil)	2.2	3.7	4.7	Food, feed, biofuel, biochemicals	Europe
Sun flower	Seed (Oil)	1.3	2.5	4.3	Food, feed, biofuel, biochemicals	USA
Sugar beet	Beet (Sugar)	45	67	85	Food, feed, biofuel	Europe
Hennep	Fibre		0.77		Textiles	China, Europe
Flax	Fibre		0.66		Textiles	Europe, China
Subtropical						
Rice	Grain (starch)				Food, feed	Thailand, Vietnam, China, India
Corn/maize	Grain (starch)				Food, feed, biofuel	USA, Europe
Sugar cane	Stems (Sugar)		71 (fresh)		Bioethanol, food, feed	Brazil, India, China
Soy bean	Grain (protein, oil)	2.9			Food, feed, biodiesel	USA, China, Brazil
Cotton	Fibre	2.0			Textiles	Australia, India, USA
Tropical						
Cassava	Tuber (starch)				Food, feed	
Oil palm	Fruits (oil)		2.9		Food, cosmetics, biochemicals, biodiesel	Indonesia, Malaysia, Nigeria
Abaca	Fibre		1.46		Yarn, ropes	Philippines, Abaca

- Agroecological zone
- Intensity of production
- Type of product

In this regard, most livestock production systems are classified into three categories:

- *Grazing-based systems*. In these livestock systems, more than 90% of feed dry mass stems from grassland. Of all the production systems, they cover the largest area: about 26% of the Earth's ice-free land surface (Steinfeld et al. 2006). This category mainly includes the keeping of ruminants in mobile or sedentary systems. Nomadic and transhumant systems have developed in regions of the world with high inter- or intra-annual variability in precipitation and/or ambient temperatures and thus plant biomass yields of grasslands. Examples include the steppes of Central and East Asia, the semiarid to arid savannahs of Africa and the highlands of Europe, the Middle East, Northern Africa and South America. Sedentary, grazing-based ruminant systems are normally found in regions with higher precipitation, lower climatic variability and higher primary production of grasslands. These include, for instance, ranching systems of North and South America and Australia characterized by large pasture and herd sizes as well as extensive, grazing-based cattle, sheep and goat systems in Europe.

- *Mixed systems*. These are the most important production system worldwide. They typically refer to mixed crop-animal systems, in which livestock by-products such as manure and draught power and crop residues are used as reciprocal inputs and where farmers commonly grow multipurpose crops (e.g. to produce grain for human consumption and stover for animal feed) (Thornton 2010). Two-thirds of the global human population live and within these systems (Thornton 2010). Mixed systems are particularly relevant in developing regions, where they produce about three-quarters each of ruminant milk and meat, 50% of pork and 35% of poultry meat (World Bank 2009).
- *Landless systems*. These systems represent livestock production units in which less than 10% of feed dry mass stems from the unit's own production (Seré and Steinfeld 1996). They are mainly pig and poultry systems. Globally, 55% of pig meat, 72% of poultry meat and 61% of eggs are produced in these systems (authors' own calculations; Steinfeld et al. 2006). A minor proportion of beef cattle stocks that are raised in so-called feedlots also belong to this category. Such landless systems are increasingly under pressure due to growing public awareness of environmental and animal welfare issues. In addition, (peri-) urban production units are commonly landless systems. Raising livestock within or in the vicinity of large human settlements provides fresh products to the markets, but also imposes health risks for humans due to the accumulation of animal wastes.

The livestock production systems described above are interrelated, and very often modifications in one system will result in concomitant modifications in another. For example, landless milk production in Kenya depends on grazing-based systems for the replacement of the milking herd (Bebe et al. 2003). Therefore, the size and number of each type of production unit influences the other. Furthermore, human population growth and societal changes put each system under pressure to adjust to evolving market demands, growing urbanization, diminishing availability of traditionally used resources and even increasing public scrutiny. Decreasing access to land and improving access to markets drive the conversion of extensive and mixed systems into more intensive production units, making these systems more efficient in the utilization of inputs to the livestock system. However, some of the systems will not be able to adapt to the new conditions and will collapse (imploding systems) (Fig. 6.10).

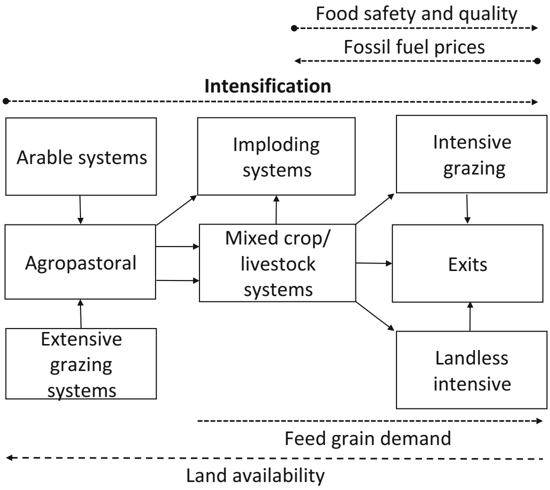

Fig. 6.10 Schematic presentation of development pathways of main livestock production systems and selected main drivers (from World Bank 2009)

Feed Resource Use in Livestock Production Systems

The feed conversion ratio (FCR) is a measure of the amount of feed (e.g. kg dry mass) needed by an animal to produce a unit (e.g. 1 kg) of meat, milk or eggs. It is the inverse of feed conversion efficiency (i.e. the ratio between the product yield and the feed input). Hence, the lower the FCR, the more efficient the conversion of feed energy or nutrients into animal products. The FCR is higher if evaluated at herd level than at the level of an individual producing animal, because the demand for feed biomass of nonproducing animals in the herd is also taken into account. The FCR varies greatly between different livestock products, production systems and regions of the world (Table 6.5). For instance, the FCRs for sheep and goat meat are more than nine times higher than for pig or poultry meat and much higher than for milk. Furthermore, the FCR is higher in grazing-based than mixed and industrial ruminant livestock systems (Herrero et al. 2013) and higher in Sub-Saharan Africa, the Caribbean, Latin America and South Asia than in North America and Europe.

This variation in FCR is mainly determined by the genetic potential of the animals and the intake, digestibility and nutrient concentrations of the available feed, with breeding and health management also playing a role. At low-feed intake level, a major proportion of the energy (and nutrients) ingested by an animal is used for maintenance purposes or is lost via urine and faeces and emission of methane, and only a minor proportion is converted into, for instance, milk or meat. However, with increasing feed intake, the proportion of feed energy (and nutrients) converted into meat, milk or eggs increases (Fig. 6.11; highlighted in green; van Soest 1994). Hence, improving energy and nutrient intakes and thus animal performance will greatly enhance the efficiency of feed resource use in livestock systems.

In line with this, the majority of monogastric livestock worldwide is kept in industrial systems, even in the less-developed countries of South and East Asia, Latin America and Sub-Saharan Africa (see above). Concentrated feeds (i.e. feeds rich in energy and/or protein and generally low in fibre, such as cereal grains and their by-products) as well as soybean and fish meal as high-quality protein sources commonly account for more than 80% of their diet (on a dry matter basis; Seré and Steinfeld 1996; Herrero et al. 2013). The high digestibility of these feeds promotes intake and animal growth rates. Consequently, the FCR in pig and poultry systems are much lower than in ruminant livestock (except dairy production) and are very similar across the various regions of the world.

Table 6.5 Feed conversion ratio for the production of milk, meat and eggs by different livestock species (in kg dry feed per kg animal product, evaluated for producing animals) (modified from Smeets et al. 2007; based on Bouwman et al. 2005; Bruinsma 2003)

Region	Milk	Bovine meat	Sheep and goat meat	Pig meat	Poultry meat and eggs
North America	1.0	26	58	6.2	3.1
Oceania	1.2	36	106	6.2	3.1
Japan	1.3	15	221	6.2	3.1
West Europe	1.1	24	71	6.2	3.1
East Europe	1.2	19	86	7.0	3.9
CIS/Baltic States	1.5	21	69	7.4	3.9
Sub-Saharan Africa	3.7	99	108	6.6	4.1
Caribbean and Latin America	2.6	62	148	6.6	4.2
Middle East and North Africa	1.7	28	62	7.5	4.1
East Asia	2.4	62	66	6.9	3.6
South Asia	1.9	72	64	6.6	4.1

CIS Commonwealth of Independent States

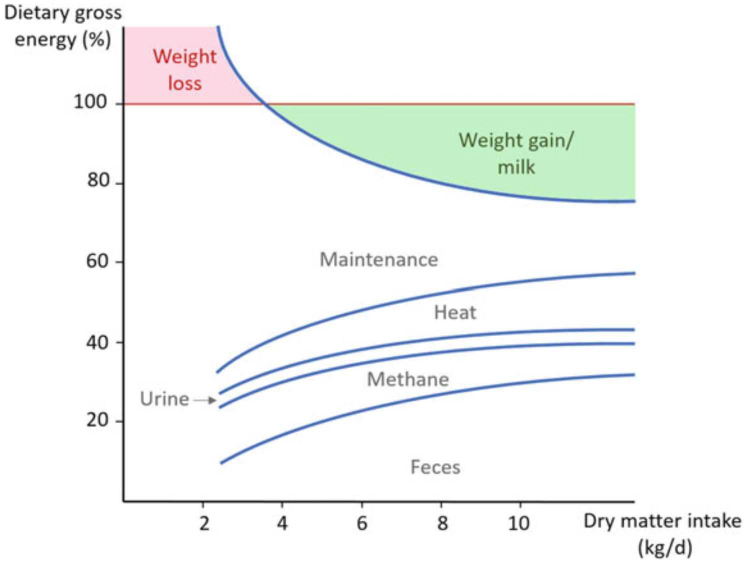

Fig. 6.11 Changes in the proportion of energy lost in faeces, urine, heat production and methane and in the proportion of energy used for maintenance and weight gain/milk production with increasing feed intake in ruminants (From van Soest 1994; based on Mitchell et al. 1932)

By contrast, ruminant feeding is much more diverse, and their diets comprise (on a dry matter basis) at least 50% roughage (i.e. bulky feeds with generally higher fibre concentrations and lower digestibility than concentrate feeds) with a few exceptions such as beef cattle finishing in feedlots. Moreover, the slower maturation and longer reproductive cycles of ruminants, as compared to pigs and poultry, result in higher proportions of nonproducing animals within the herds. Consequently, the FCR at both the animal and system level is higher in ruminant than in monogastric livestock. The FCR in milk production is lowest. Because milk contains about 85% water, its nutrient and energy density is very low compared to other animal-derived food products. While most ruminant livestock in industrialized countries is kept in mixed systems (Seré and Steinfeld 1996) where feeding is based on cultivated forage and concentrate feeds, animals in other regions of the world commonly graze on (semi-)natural grasslands or are fed crop residues, and use of concentrate feeds is lower. These differences in diet composition and hence performance of animals are responsible for the differences in the FCR of ruminant products between the various production systems and regions of the world.

Box 6.3: Feed Conversion Ratio (FCR)
Common approaches to evaluating the FCR and ecological footprints of livestock systems do not differentiate between the types of plant biomass used as feed. For instance, the use of feed resources inedible for humans, such as roughage and crop residues, may reduce competition with plant biomass as food or feed. When expressed as the amount of energy and protein from human-edible feeds per unit of animal product, differences in FCR between livestock products become much smaller, because ruminant diets typically contain lower proportions of feeds suitable for human consumption. In some cases, the FCR is even lower for the production of beef than for pork, poultry meat and eggs (Wilkinson 2011). Similarly, these approaches only focus on either milk, meat or eggs as primary products and do

(continued)

Box 6.3 (continued)

not (adequately) account for other outputs or services provided by livestock. For instance, animal manure is an important source of nutrients for the maintenance of soil fertility in crop production, in particular in mixed farming systems of Sub-Saharan Africa, Latin America and South and East Asia. Neglecting this additional output overestimates the actual FCR in mixed systems. Also, calves born in dairy cattle systems are also raised to produce meat. Correcting for the greenhouse gases emitted during the production of the same amount of meat in specialized beef cattle systems considerably reduces the carbon footprint of cow milk (Flysjo et al. 2012) and diminishes the differences between various production systems.

As the vast majority of expenses in livestock husbandry comes from the provision of animal feed, the FCR greatly determines the profitability of livestock farming. Moreover, the FCR is a key determinant of the demand for natural resources and the emissions of environmental pollutants in livestock systems. For instance, about 98% of the water needed to produce animal products (i.e. water footprint) is related to the production, processing, transport and storage of feed for livestock, whereas only 1% each is needed as drinking or service water (Mekonnen and Hoekstra 2010). Accordingly, the water footprints of beef, mutton and goat meat are higher than of pig and poultry meat and are even higher in grazing-based than in mixed or industrial ruminant systems, in particular those of Europe and North America characterized by a lower FCR. There are similar differences in the carbon footprint of animal products (Herrero et al. 2013). Hence, any improvements in the FCR will greatly contribute to increasing profitability and reducing environmental emissions and (natural) resource use in livestock farming.

6.1.11 Towards Sustainable (Intensification of) Agriculture

In the bioeconomy, agriculture needs to be performed sustainably. This requires a definition and characterization of sustainable agriculture. One approach is to categorize farming systems according to their management concepts (see Fig. 6.12). Industrial farming aims to maximize economic benefit through a high level of mechanization and the application of synthetic pesticides and fertilizers for crop production and through the utilization of specialized breeds and intense feeding, health and reproductive management for animal production. Integrated farming uses both synthetic and biological means of nutrient supply and pest control, but applies input and management measures at levels considered economically justified and that reduce or minimize ecological and health risks. Additionally, integrated farming makes use of naturally occurring strengths in plants and animals used for production purposes, like resistance to drought in certain crops or tolerance to diseases and parasites in certain animal breeds. The conservation of natural resources, including genetic resources, is at the focus of both organic farming and conservation farming. In organic farming, no synthetic fertilizers, pesticides or feed supplements are allowed. Conservation farming mainly focuses on agronomical practices that enhance soil conservation via, e.g. cover crops or incorporation of crop residues into the soil; here there might be a conflict with livestock in mixed production systems because livestock will compete for crop residues as feed and may compromise the objectives of conservation agriculture. Finally, precision farming strives to minimize agricultural inputs by applying spatially specific management to crops and accurate and timely feeding to animals using modern agricultural technologies including digitalization (see Box 6.4). All these farming concepts apply management rules to define and operationalize sustainable agricultural management.

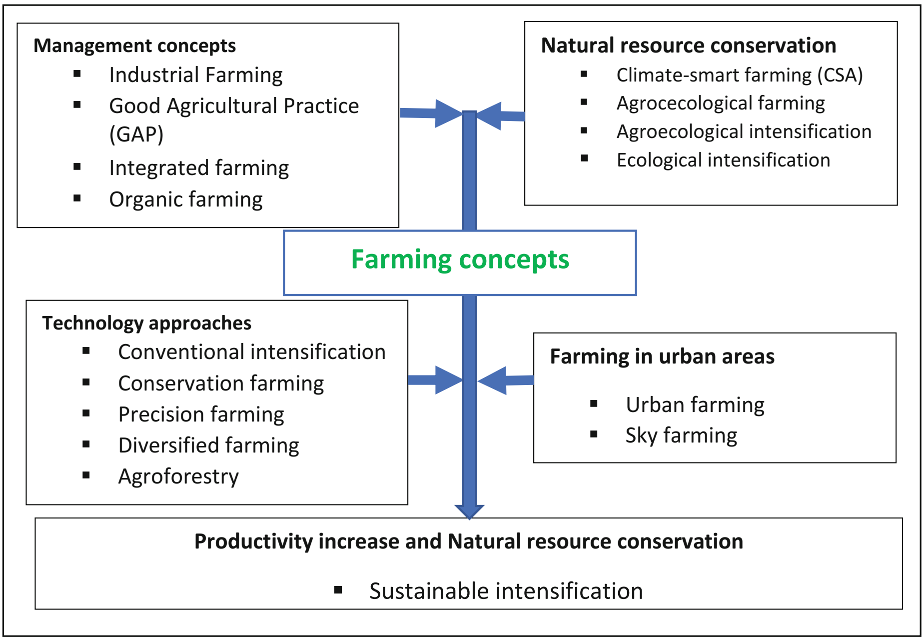

Fig. 6.12 Farming concepts

Box 6.4: Farming Concepts with a Clear Definition (Rather Than a Conceptual Approach)

Good Agricultural Practice (GAP)

'Good Agricultural Practice (GAP), for instance in the use of pesticides, includes the officially recommended or nationally authorized uses of pesticides under actual conditions necessary for effective and reliable pest control. It encompasses a range of levels of pesticide applications up to the highest authorized use, applied in a manner which leaves a residue which is the smallest amount practicable' (FAO and WHO 2014). With respect to, for instance, health management in livestock farming, GAP includes the prevention of entry of diseases onto the farm, an effective health management (e.g. record keeping, animal identification and monitoring) and the use of chemicals and medicines as described (IDF and FAO 2004).

In the EU, 'good farming practice' (GFP) is used synonymously with GAP. National codes of GFP constitute minimum standards for farm management and serve as a precondition for payments to farmers in the context of 'cross-compliance'. Cross-compliance is the attachment of environmental conditions to agricultural support payments (Baldock and Mitchell 1995) and is an obligatory element of the Common Agricultural Policy (CAP). In the EU, cross-compliance as well as GAP rules are generally laid down in laws or legal guidelines.

Integrated Farming

Integrated farming seeks to optimize the management and inputs of agricultural production in a responsible way, through the holistic consideration of economic, ecological and social aspects. This approach aims at minimizing the input of agrochemicals and medicines to an economical optimum and includes ecologically sound management practices as much as possible. As one example, 'Integrated Pest Management (IPM) means the careful consideration of

(continued)

Box 6.4 (continued)

all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human and animal health and/or the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms' (FAO and WHO 2014). Moreover, the close linkage of crop and livestock components in agroecosystems allows for efficient recycling of agricultural by-products or wastes, thereby reducing the reliance on external inputs such as fertilizers or animal feeds.

Organic Farming

'Organic Agriculture is a production system that sustains the health of *soils, ecosystems* and *people*. It *relies on ecological processes, biodiversity and cycles adapted to local conditions*, rather than the use of inputs with adverse effects. Organic Agriculture combines *tradition, innovation* and *science* to benefit the shared environment and promote *fair relationships* and a good *quality of life* for all involved' (IFOAM 2005). There are several variants of organic agriculture, including livestock organic production. All of them forbid the use of synthetic pesticides and fertilizers in crop production. Crop nutrient demands and crop health are managed through biological methods of N fixation, crop rotation and the application of organic fertilizer, especially animal manure. Regarding livestock, organic production fosters the welfare of animals, and it restricts the use of synthetic feed supplements to those conditions where the welfare of the animal might be compromised by a serious deficiency. Similarly, organic livestock production focuses on disease prevention, and it prohibits the use of antibiotics, unless any other option is available to stop the animal from suffering.

Precision Farming

Precision farming is a management approach based on the spatially specific and targeted management of agricultural land and fields. It makes use of modern agricultural production technology and is often computer-aided. In crop farming, the objective of precision farming is to take account of small-scale differences in management demand within fields. Sensors that assess the nutritional status and health of crops support their spatially differentiated management. Similarly, precision farming in livestock production aims at (continuous) monitoring of, for instance, the nutrition, performance, health and reproductive status of (individual or small groups of) animals in real-time. Such information helps farmers to make appropriate decisions in animal, feed or grazing management to optimize production, health and welfare of animals but also to increase efficiency of natural resource use in and reduce environmental impact of livestock farming.

Conservation Farming

'Conservation Agriculture (CA) is an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:

- Continuous minimum mechanical soil disturbance.
- Permanent organic soil cover.
- Diversification of crop species grown in sequences and/or associations' (FAO 2017a).

In a future bioeconomy, agriculture will need to make combined use of all available knowledge and technology that can help increase productivity while, at the same time, reducing the negative environmental impacts of agricultural production. This vision is also described as ‘sustainable intensification’ (see Box 6.4).

Box 6.5: Sustainable Agricultural Intensification

The Royal Society (2009) defined sustainable intensification as a form of agricultural production (both crop and livestock farming) whereby ‘yields are increased without adverse environmental impact and without the cultivation of more land’. More recently, Pretty et al. (2011) extended this definition of sustainable agricultural intensification to ‘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’.

Box 6.6: Sustainable Intensification of Livestock Production

Examples of India and Kenya show that small changes in feeding practices like balancing diet with the same feed ingredients, feeding small additional amounts of concentrate and introducing cooling systems can greatly increase yields and total animal production and the sustainability of the production systems (Garg et al. 2013; Upton 2000).

There is evidence that the nutrient-use efficiency increases, while the intensity of methane emissions (g/kg milk) decreases by feeding nutritionally balanced rations designed from locally available resources in smallholders of cattle and buffaloes (Garg et al. 2013).

Even though challenging, larger improvements can be made in those production systems where the animal is still far from reaching its genetic potential for production, like those typically found in tropical and in developing regions.

Other intensification option is the more systematic use of agricultural or industrial by-products. However, one main problem of these materials is the unknown content of nutrients, therefore, a characterization of the available resources per region and their feeding value for each species may help to introduce them as ingredients in animals’ diets. In this regard, even at the production units with high levels of intensification, advances towards sustainability can be made. In recent years the inclusion of citrus by-product from the juice industry has been regularly practised in dairy cattle diets.

Moreover, later examples have shown that small proportions of crop residues like wheat straw and corn stover—as source of physically effective fibre—can be included in diets of high-yielding dairy cows without negative impacts on yields (Eastridge et al. 2017). Such by-products have been traditionally assumed not to be suitable for diets of high-yielding animals and have been rather associated in mixed systems with less productive animals.

The use of local forages as source of protein can also aid to the sustainable intensification of production systems. However, for a farmer to adopt any management practice, this has to fit into the farmer’s daily routine or only minimally alter it; additionally, it should allow the farmer to afford it.

In order to define and describe the goals of sustainable agriculture, relevant criteria need to be established. Discussions in various international, multi-stakeholder roundtables have led

Table 6.6 Summary of criteria for sustainable agricultural production and biomass supply, compiled from the sustainability studies of the Roundtable on Sustainable Palm Oil (RSPO), the Round Table on Responsible Soy (RTRS), Bonsucro and the Roundtable on Sustainable Biomaterials (RSB) (from Lewandowski 2015)

Social criteria
Respect of human and labour rights
– No child labour
– Consultation/stakeholder involvement
– Payment/fair salary
– No discrimination (sex, race)
– Freedom of association
– Health and safety plans
– Respect of customary rights and indigenous people
Smallholders' rights
Responsible community relations
Socio-economic development
Well-being
Ecological criteria
Protection of biodiversity/wildlife/HCV areas
Environmental responsibility
– Minimization of waste
– Reduction of GHG
– Efficient use of energy
– Responsible use of fire
Soil degradation
Water resources/quality
Air pollution
Use of best practice/responsible agricultural practices
– Responsible use of agrochemicals
– Training of employees
Responsible development of infrastructure and new areas of cultivation/plantations
– Impact assessment prior to establishment
– No replacement of HCV areas after year X
– No establishment on fragile soils
– Restoration of degraded land
– Compensation of local people, informed consent
– Maintenance of sites with high-carbon soil content
General and economic criteria
Commitment to continuous improvement
Wise use of biotechnology
Climate change and GHG mitigation
Food security
Use of by-products
Traceability
Transparency
Legality
Responsible business practices
Respect for land-use rights

to a set of internationally accepted criteria being compiled. The general criteria of the sustainability standards elaborated by these roundtables are shown in Table 6.6.

However, even if we manage to set the criteria for sustainable agriculture, the aspiration of 'absolute' sustainability appears inoperable. This is because the manifold trade-offs between sustainability goals and conflicting stakeholder perceptions of sustainability render the simultaneous fulfilment of all sustainability criteria shown in Table 6.6 impossible. Therefore, the concept of sustainable agricultural intensification will need to strive for the best possible compromise between productivity increase and natural resource conservation.

There are many options for increasing agricultural productivity. Figure 6.13 shows the numerous technical approaches that can contribute to this goal. These include breeding of efficient crop varieties and animal breeds; development of efficient, site-specific crop and livestock management and land-use systems; development of specific feeding strategies for an animal type and region (see Box 6.6); logistic optimization; and exploration of new biomass resource options, such as algae and biomass from permanent grasslands.

The largest potential for maximizing yields through improved cropping and livestock systems is seen in approaches targeted at closing the yield gap between achievable and actually harvested yields. In many regions of Africa, Latin America and Eastern Europe, this gap averages up to 55% (FAO 2002). The problem is often not the biophysical suitability of the site, 'site x crop combination' or production potential of livestock animals but insufficient agronomical practices and policy support (Yengoh and Ardo 2014). However, to avoid the intensification of agricultural production necessary to exploit the yield gap becoming, or being perceived as, ecologically 'unsustainable', concepts for 'sustainable intensification' need to be elaborated. In addition, advanced agricultural technologies, such as precision farming (Box 6.4), that can improve productivity without negative ecological impacts, need to be further developed.

Crop and animal breeding

- Improved crops and varieties
  - Higher yield and optimized quality
  - Improved efficiency (use of water, nutrients)
  - Stress tolerance (biotic and abiotic stress)
  - Efficient photosynthesis, C4 pathway
  - Improved plant architecture
  - Higher yields of by-products and residues
  - Perennial crops
- Animal breeds with high feed-use efficiency
- Development of new biogenic resources, such as algae

Crop management and farming systems

- Development of site-specific crop management systems with optimal combinations of: crop choice, variety choice, soil cultivation, crop establishment, fertilization, irrigation, and crop protection regimes
- Development of efficient, low-input, low-emission, soil-conserving cropping systems (sustainable intensification, precision farming, low-intensity soil tillage or no-till, integrated crop protection and production systems)
- Soil improvement and reclamation (e.g. phytoremediation, biochar)
- Participation and training of farmers in development and implementation of improved management systems
- Access for farmers to modern varieties, fertilizer, and crop protection
- Access for farmers to local and regional markets
- Strengthening the rights of smallholder farmers
- Integrated “Food-Feed-Fuel-Fibre” and “animal-crop-bioenergy” production systems and multi-product use of crops
- Urban farming

Land-use systems

- Multiple land-use systems
- Perennial land-use systems
- Maintenance and use of grassland systems
- Amelioration and use of marginal and degraded land
- Bottom-up, participatory approaches to land-use planning

Harvest, transport, pre-treatment, storage

- Improved supply chain logistic
- Availability of transport, pretreatment and storage infrastructure, infrastructural investments
- Reduction of harvest, transport, treatment, and storage losses

Conversion

- Exploitation of residue and by-product streams, closing nutrient cycle
- Efficient biomass use
- Reduction of food wastes
- Allocation of biomass to most sustainable uses

Biomass and product use

- Efficient biomass conversion systems
- Efficient bioenergy technologies
- Biorefineries, different uses of biomass components
- Cascading: material followed by or combined with energetic use

Fig. 6.13 Technical and socio-economic options for mobilizing the sustainable biomass potential, allocated to different production scales in the bio-based value chain (from Lewandowski 2015)

The provision of technical solutions for the improvement of cropping and livestock systems alone will, however, not be sufficient to mobilize the sustainable biomass supply. Farmers must also be willing to adopt these solutions and see an advantage in their application (Nhamo et al. 2014). Also, farmers must be able to afford the agricultural inputs required and be in a position to apply them. This calls for support through credit programmes and access for farmers to markets and training programmes (Nhamo et al. 2014).

Agriculture and Greenhouse Gas (GHG) Emissions

Agriculture also needs to contribute to climate change mitigation via a reduction of greenhouse gas (GHG) emissions. The main GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Presently, global agriculture emits about 5.1–6.1 Gt $CO_{2\text{equivalents}}$ of GHG a year (Smith et al. 2007). CO_2 is mainly released from microbial decay or burning of plant litter and soil organic matter and also comes from the use of fossil resources in agricultural production. CH_4 is mainly produced from fermentative digestion by ruminant livestock, from the storing of manure and from rice grown in flooded conditions (Mosier et al. 1998). N_2O comes from nitrification and denitrification of N in soils and manures, or from N volatilization, leaching and runoff, and its emission is enhanced with higher levels of N fertilization (for soils) or high levels of N feeding (for animals) (IPCC 2006).

The global technical potential for GHG mitigation in agriculture is estimated to be in the range of 4.5–6.0 Gt $CO_{2\text{equivalents}}$/year if no economic or other barriers are considered (Smith et al. 2007). In general, GHG emissions can be reduced by increasing plant and animal productivity (i.e. unit of final product per unit of area or per animal) and by more efficiently managing inputs into the system (e.g. applying the appropriate amount of fertilizer needed for a particular crop under the soil/climatic conditions, closed nutrient cycling). Other options include land management that increases soil carbon sequestration (e.g. agroforestry), improving diet quality to reduce enteric CH_4 formation, soil management that enhances the oxidation of CH_4 in paddy fields and manure management that minimizes N_2O formation. Finally, also the use of bioenergy is a mitigation option (see Fig. 6.14; for details

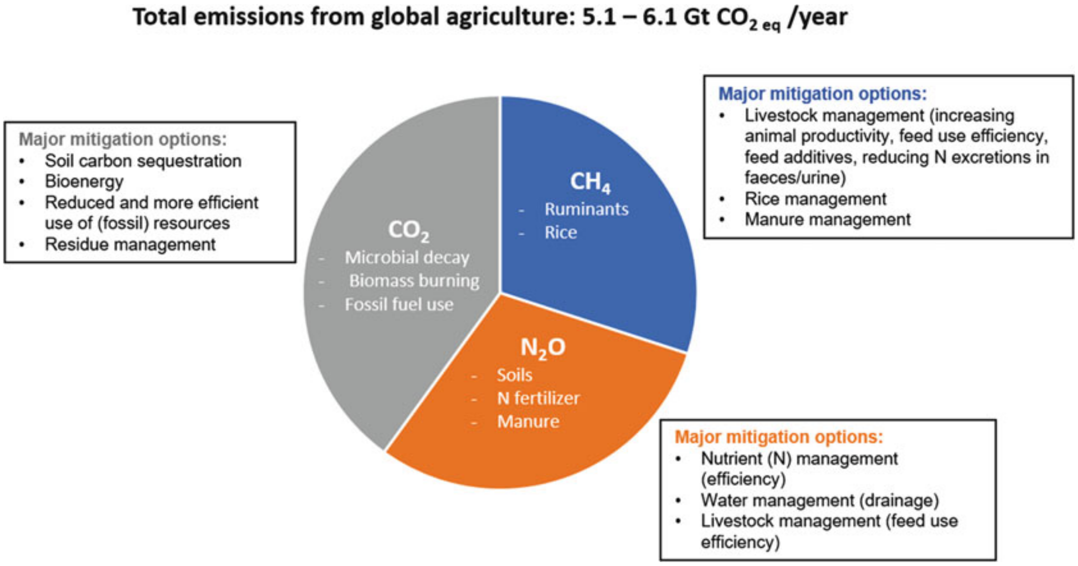

Fig. 6.14 Greenhouse gas emissions from global agriculture in Gt $CO_{2\text{equivalents}}$/year together with major emission sources. Boxes indicate major GHG mitigation options in agricultural management (data from Smith et al. 2007)

on agricultural GHG mitigation options, see Smith et al. 2007).

Review Questions

- What are the main determinants for the kind of agricultural production performed?
- What are the management options for improving productivity in crop and animal production?
- What is sustainable agriculture and sustainable intensification?
- How can negative environmental impacts of agricultural production be minimized?

Further Reading

For statistics of agricultural production, see FAOSTAT (http://www.fao.org/faostat/en/#home) and USDA (https://www.usda.gov/topics/data)

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6.2 Forestry

Gerhard Langenberger and Melvin Lippe

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Abstract Forests cover about 30% of the Earth's total land area, harbouring most of the world's terrestrial biodiversity and containing almost as much carbon as the atmosphere. They have many functions, providing livelihoods for more than a billion people, and are of high relevance for biodiversity conservation, soil and water protection, supply of wood for energy, construction and other applications, as well as other bio-based resources and materials such as food and feed. The forestry sector was the first to adopt a sustainability concept (cf. Carlowitz), and sustainable use and management of forests remains an important issue to this day. Forestry is a multifunctional bioeconomic system and has an important function in securing the sustainable resource base for the present and future bioeconomy.

Keywords Forest distribution; Forest types; Natural forests; Planted forests; Forest products; Forest management

Learning Objectives
After studying this chapter, you should:

- Have gained an understanding of forests as distinct ecosystems
- Be aware of the multiplicity of functions and services which forests provide or safeguard
- Be able to explain why forests are an important multifunctional eco- and production system and how they contribute to the maintenance of ecosystem services, such as biodiversity protection and climate change mitigation
- Have gained an overview of the major forest types and their distinctive features

- Be aware of the characteristics and specifics of forest management
- Understand the relevance of forests for the bioeconomy

6.2.1 Forestry and Forests

Forestry is the practice and science of managing forests. This comprises the exploitation of both natural and near-natural forests. Near-natural forests are those where the original tree species composition is still apparent and the original ecosystem dynamics have been maintained, at least to some extent. The artificial establishment of forests following either recent or historical removal of the original forest cover ('reforestation' or 'afforestation') is also becoming increasingly important. This can be done with native tree species, which were part of the original forest cover, or with so-called exotic species—species from other ecosystems and often even continents. Forestry thus comprises the utilization, management, protection and regeneration of forests.

It is common understanding that forests are composed of trees. But when can an aggregation of trees be called a forest? Are trees along a road—an avenue—already a forest? Are Mediterranean olive groves or *Eucalyptus* plantations forests? Can recreational parks with scattered trees, e.g. 'Central Park' in New York and the 'English Garden' in Munich, be defined as forests? At first glance, this might not be of relevance since the purpose of such areas is obvious—they are not used, e.g. for timber production. Nevertheless, other areas covered by trees may not be defined as parks, but still fulfil similar important protection tasks or recreational purposes, such as Frankfurt's city forest (Frankfurt a.M. 2017). Therefore, a general definition of a forest could include the following criteria:

- Forests are an accumulation of trees, which are lignified, erect, perennial plants.
- They develop a 'forest climate', which differs considerably from the open land and is characterized by much more balanced temperature fluctuations and extremes, reduced wind speeds and a higher relative humidity.
- This results in characteristic soil properties with usually high-soil organic matter contents.
- The different forest types with their characteristic vertical structures provide a multitude of habitats and ecological niches supporting diverse plant and animal communities.

Since forests play an important role in the bioeconomy, for carbon storage and thus for climate change mitigation measures, a more technical definition is required, which can be used for analyses and statistics. For this reason, the FAO lay down criteria to define forests, which can be found in Box 6.7:

Box 6.7: Forest Definition According to FAO (2000) (Shortened and Simplified)

- Covers natural forests and forest plantations, including rubber wood plantations and cork oak stands.
- Land with a *tree canopy* cover of more than *10%* and an *area* of more than *0.5 ha*.
- Determined both by the presence of trees and the absence of other predominant land uses (cf. agriculture).
- Trees should be able to reach a *minimum height of 5 m.*
- Young stands that have not yet but are expected to reach a crown density of 10% and tree height of 5 m are included under forest, as are temporarily unstocked areas.

(continued)

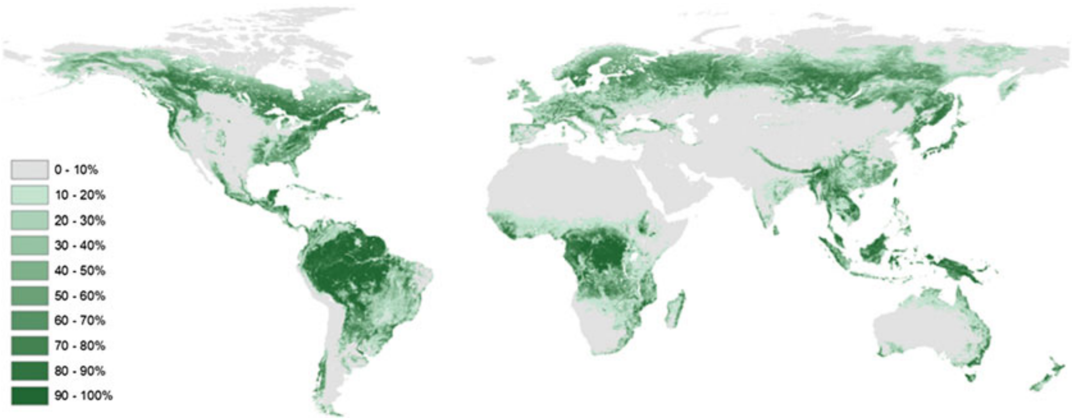

Fig. 6.15 Global extent of forest areas (based on FAO 2010)

Box 6.7 (continued)

Excludes:

- Stands of trees established primarily for agricultural production, for example, fruit tree plantations, and also agroforestry systems or short rotation coppice plantations.

6.2.2 Forest Distribution, Floristic Regions and Forest Types

6.2.2.1 Global Forest Distribution

Most regions of the Earth with a suitable climate (sufficient water availability and minimum length of growing season) were originally covered by forest. Since humans began to colonize the planet, forests have been exploited for resources and cleared, especially for agricultural production (cf. Albion 1926). Figure 6.15 provides an overview of the global distribution of forests, and Table 6.7 shows the forest cover by region. In Fig. 6.16, the countries with the largest forest areas are listed.

Table 6.7 Global forest area and regional distribution (based on FAO 2015a)

	Forest area	
Region/subregion	1000 ha	% total forest area
Eastern and Southern Africa	267,517	7
Northern Africa	78,814	2
Western and Central Africa	328,088	8
Total Africa	674,419	17
East Asia	254,626	6
South and Southeast Asia	294,373	8
Western and Central Asia	43,513	1
Total Asia	592,512	15
Russian Federation (RUF)	809,090	20
Europe excl. RUF	195,911	5
Total Europe	1005,001	25
Caribbean	6933	0
Central America	19,499	0
North America	678,961	17
Total North and Central America	705,393	17
Total Oceania	191,384	5
Total South America	864,351	21
World	4033,060	100

6.2.2.2 Floristic Kingdoms and Forest Types

There are several approaches to distinguish and classify the natural vegetation of the Earth. A key criterion of all approaches is the floristic distinctiveness of an area. A major classification of the Earth's vegetation based on the endemicity and the presence or absence of taxa is the formulation of floral kingdoms, a concept first suggested by Good (1947) and later elaborated by Takhtajan (1986). This concept distinguishes

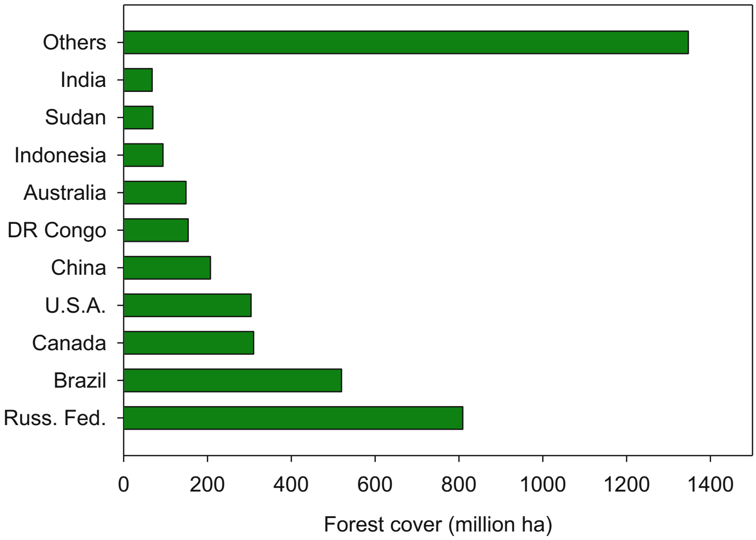

Fig. 6.16 The most important countries in terms of forest area (based on FAO 2015a, b)

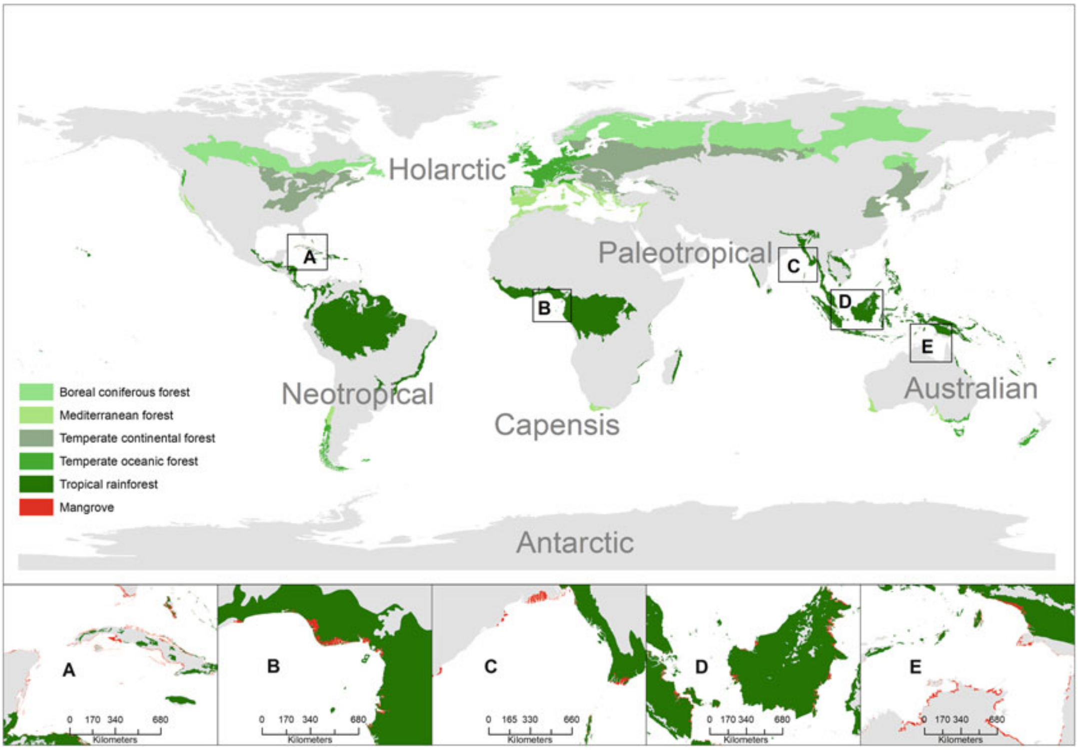

Fig. 6.17 Floristic kingdoms and global extent of important forest types (based on FAO 2010; Giri et al. 2010)

six floral kingdoms—the Holarctic, Neotropical, Paleotropical, Australian, Capensis and Antarctic kingdoms (see Fig. 6.17)—which are further subdivided into floristic regions and provinces. Since the floral kingdoms represent major species groups, they also give an indication of the general usability of the associated forests and thus reflect the bioeconomical potential.

The following overview of the floristic kingdoms lists plant groups of major economic importance together with their common use:

Holarctic

The Holarctic comprises the vegetation in the Northern Hemisphere beyond the tropics and subtropics. The forest types included are the boreal and temperate forests (see below). This huge area is characterized by representatives of important timber-tree families, such as the pine family (Pinaceae) with, e.g. firs (*Abies* spp.), spruces (*Picea* spp.), larches (*Larix* spp.) and pines (*Pinus* spp.), and several broad-leaved tree families such as the beech family (Fagaceae) with beech (*Fagus* spp.), oak (*Quercus* spp.) and chestnut (*Castanea* spp.). Other important timber families are the birch family (Betulaceae) with birch (*Betula* spp.), alder (*Alnus* spp.) and hornbeam (*Carpinus* spp.) and the willow family (Salicaceae) with poplar (*Populus* spp.) and willow (*Salix* spp.). The Holarctic is also a centre of diversity of the rose family (Rosaceae) with its cherries (*Prunus* spp.), apples (*Malus* spp.) and peaches (*Pyrus* spp.). The *Prunus* spp. in particular play an important role in a forest bioeconomy as source of valuable hardwood.

Neotropical

The Neotropical kingdom mainly covers Central and South America. It is of crucial importance as source of food plants such as tomato and pineapple (cf. Vavilov Centers) (Hummer and Hancock 2015). Nevertheless, it is also home to a range of highly valued hardwoods, e.g. true mahogany (*Swietenia mahagoni*) (cf. Anderson 2012), as well as the major provider of natural rubber, the Pará rubber tree (*Hevea brasiliensis*).

Paleotropical

The Paleotropical kingdom covers the huge and very diverse, mainly tropical area from Africa to Southeast Asia. It is particularly important as the origin of the Dipterocarpaceae family, a timber-tree family with several hundred species. This family is the source of important tropical timbers such as meranti, kapur, balau, etc. (Wagenführ 1996). The Combretaceae are another plant family with important timber trees including, for example, *Terminalia* spp. (framiré, limba). The Paleotropical kingdom is also the centre of diversity of the figs (Moraceae).

Australian

The Australian kingdom is the origin of important plantation-tree species, especially *Eucalyptus* spp. (Myrtaceae family). These are a crucial source of pulpwood. In addition, it is a centre of diversity of *Acacia* spp. (Fabaceae family), which also play an important role in tropical tree plantations.

Capensis

The Capensis is of more importance as source of ornamentals than for forestry. It is a centre of diversity of the heath family (Ericaceae).

Antarctic

The Antarctic kingdom includes one tree group of mainly regional importance to a forest bioeconomy, the southern beeches (*Nothofagus* spp.).

The Major Forest Types

While plant kingdoms refer to taxonomic distinctiveness and thus reflect evolutionary processes rather than habitat homogeneity, forest types reflect environmental conditions and are therefore an important classification for ecology, productivity and management options (Table 6.8).

Boreal Forests

Boreal forests cover about 13% of the Earth's land surface. They are found in the Northern Hemisphere, mainly between 50° and 70° north, and comprise the huge conifer-dominated forests of northern Europe, northern Russia, Canada and Alaska, also known as taiga. In the south, they merge with the temperate-mixed and broad-leaved forests. Climatically, they are cold-humid with annual precipitation between 250 and 500 (750) mm, mainly occurring during summer. Despite the regionally very low precipitation, the hydrological balance is usually positive due to

Table 6.8 Total biomass dry matter stock per hectare and net primary production of different forest types (cited in Richter 2001; Busing and Fujimori 2005[a])

Forest type	Dry matter stock per hectare/tonnes	Net primary production/g m^{-2} $year^{-1}$
Boreal forest	60–400	363–870 (1050?)
Temperate forest	150–500	1090–1775
Temperate pine forest, Oregon, USA	850	1890
Temperate redwood rainforest, California, USA[a]	3300–5800	600–1400 (only aboveground NPP)
Tropical rainforest	200–800 (1100)	3500
Mangroves	-	1700

Fig. 6.18 Large, homogenous tracts of pine forests interspersed with e.g. aspen are a typical feature of the boreal forest (left); fire plays a considerable role in nutrient cycling and forest regeneration (right) (Photos: G. Langenberger)

low evapotranspiration. The area is characterized by extreme temperature fluctuations, with permafrost soils where the average annual temperature drops below 0 °C. The vegetation period is on average 3–5 months, with a maximum of 6 months. The resulting forests are more or less single-layered with a maximum tree height of up to 20 m. It is comparatively poor on species and dominated by pine trees (*Pinus* spp., *Picea* spp., *Larix* spp., *Abies* spp.) and wind-pollinated broad-leaved trees (*Betula* spp., *Populus* spp.). The undergrowth is dominated by dwarf shrubs (e.g. *Vaccinium*), mosses and lichens. Ectomycorrhiza plays a crucial role in this type of ecosystem. Since these forests usually cover old landmasses, such as the Canadian shield, the soils are rather poor (e.g. podzols), and considerable surface humus layers (cf. the occurrence of mosses and *Vaccinium*) can be found. Fire plays a considerable role in these forests. It transforms the accumulated biomass into nutrient-rich ashes and thus initiates the natural regeneration of the forests (Fig. 6.18). Due to their homogeneity and species composition, these forests are an important resource for pulp and paper production.

Temperate Forests

Temperate forests cover about 8% of the Earth's land surface. As with boreal forest, they mainly occur in the Northern Hemisphere. They can be found between 35° and 55°, depending on macroclimatic conditions. The mountain forests of Patagonia and New Zealand can be named as examples of temperate forests in the Southern Hemisphere. Temperate forests are characterized by more balanced climatic conditions than boreal forests. They are humid with precipitation between 500 and 1000 mm/year and rainfall maximum in summer. They experience frost periods, but with much less pronounced extremes. The average annual temperature ranges between 5 and 15 °C, and the vegetation period lasts between 5 and 8 months. They show a pronounced seasonality, often with gorgeous autumn colours, e.g. during the 'Indian summer' in north-eastern USA and Canada.

Temperate forests display a high diversity of, in particular, deciduous broadleaf trees, but also evergreen trees, which can attain considerable dimensions. Tree heights of 50 m have been documented for firs, Douglas firs, oaks and beeches, even in Germany. Economically important species include oaks, beeches, maples, basswood, poplars, cherries, hickories, tulip trees, etc. Conifers such as spruce, fir and pine play an important economic role locally as planted forests. Ecologically, these forests are not only rich in tree species, but are also often characterized by a distinct shrub and herb flora. Geophytes are a typical feature of temperate forests. Two structural layers can often be distinguished. Temperate forests are not homogenous but display a high diversity of tree types depending on local site and microclimatic conditions (Arbeitsgemeinschaft Forsteinrichtung 1985). Another important difference between boreal and temperate forests is the prevailing soil types. Temperate forests mainly grow on young, post-glacial soils, often brown soils. Economically, temperate forests are still important providers of pulp wood, and especially construction timber. The production of maple syrup in eastern North America and of honey in fir forests ('Tannenhonig') can also be mentioned as specialized uses of temperate forests.

The coastal temperate rainforests of the North American West Coast represent a special case of temperate forest. They occur from Alaska down to California along the Pacific coast and its mountain ranges and are characterized by mild winters and moderate summers accompanied by high precipitation. They are dominated by conifers, comprising some of the most impressive tree species in the world including redwood (*Sequoia sempervirens*) (Fig. 6.19), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*) and Douglas fir (*Pseudotsuga menziesii*). These forests are of considerable economic importance for the timber industry and are intensively exploited. Most of these species have been tested as exotics in Germany, but only Douglas fir has been established as a common component of German forests. Today it plays a considerable economic role.

Mediterranean Forests

Mediterranean forests are defined by a set of climatic conditions rather than the locality. As such, they not only occur around the Mediterranean

Fig. 6.19 Redwood (*Sequoia sempervirens*) in a Californian national park (note the relative height of the human) and the common clear-cutting practice of West Coast forests in Oregon (Photos: G. Langenberger)

Sea but also in South Africa, California, central Chile and Southern Australia. The respective climate is characterized by mild, rainy winters and very hot, dry summers. The vegetation is sclerophyllous; the trees are evergreen. Although the forests around the Mediterranean Sea were degraded hundreds of years ago, some economically important forest products still play a role to date. The olive tree (*Olea europaea*) provides fruits and oil and is also regarded as a popular timber source. The cork oak (*Quercus suber*) not only produces cork for corking wine bottles but also for use as a very good flooring material. Cork oak stands are formally classified as forests by FAO (2000). The pine *Pinus pinea* produces the pine nuts (pignoli nuts), which are actually pine seeds, used in modern cuisine, for example, in pestos. The argan tree (*Argania spinosa*) of Morocco has recently attracted attention through its oil, which is traded as Argan oil and used in cosmetics but also as a food oil. Historically, the Lebanon cedar (*Cedrus libani*), which was already mentioned in the Old Testament, played an important role as valuable timber source in the Middle East. One of the most important plantation trees, the Monterey pine (*Pinus radiata*), actually originates from California, where it did not play a considerable role. But it proved to be a high-potential plantation species outside its natural habitat.

Tropical Rainforests

Tropical rainforests are the world's most diverse forests. While the climatic conditions in these forests are more or less similar around the world, structure, species composition and usability display distinct differences. Tropical rainforests are characterized by average temperatures between 24 and 30 °C and a minimum average annual temperature of 18 °C. Rainfall exceeds 1800 mm per year. The vegetation is dominated by a high diversity of woody plants, which can attain considerable heights of 30–50 m, sometimes even 70 m. Due to the high diversity, the density of individual species are usually very low, the exception being the dipterocarp forests of Southeast Asia. The high species diversity is also reflected in the structural diversity and associated ecological niches. A common misunderstanding is that tropical rainforests are impenetrable jungles. The opposite is the case, at least in undisturbed forests. Due to the shade created by the high and dense canopy, only little undergrowth develops, and it is easy to walk through the stands.

Three major tropical rainforests are usually distinguished: the American rainforest, mainly comprising the Amazon and Orinoco basins, the Indo-Malayan and Australian rainforest and the African rainforest. All of them are considered important timber sources.

Mangroves

Mangroves (Fig. 6.20) are forests growing in the intertidal zone of tropical and subtropical coastlines, estuaries and deltas (cf. 'Sundarbans' in Bangladesh; see also Fig. 6.17 A–E). Their adaption to regular inundation by saltwater is unique and requires tolerance to salt as well as oxygen shortage (cf. stilt roots, pneumatophores). They are found throughout the tropics and subtropics. Depending on the coastline and tidal dynamics, there can be a distinct zonation of species. Mangroves have been and, in some regions, still are a considerable source of timber, firewood and charcoal as well as tannins. They are of importance as a food source for fish and shells. With their zonation of different tree species, which often stretch a considerable distance into the sea, mangroves can protect shorelines and play an important role in coastal nutrient cycling and as spawning grounds for fish, which find protection in the shallow water and between the often impenetrable stilt roots of, for example, the *Rhizophora* trees. Due to the past heavy exploitation, these functions and services are often obsolete nowadays. Mangroves continue to be threatened by transformation into fishponds, rice fields, resorts and so on.

6.2.2.3 Natural and Planted Forests

Forests regenerate themselves naturally either through succession (cf. pioneer species) following a major disturbance (fire, storm, etc.) or less

Fig. 6.20 Mangroves are an impressive feature of many tropical coastlines (Island of Leyte, Philippines) (Photo: G. Langenberger)

obviously by the replacement of single trees or tree groups in gaps (cf. Box 6.8) after natural mortality or smaller disturbances (lightning, local storm damage, etc.). The same processes more or less apply to human-caused disturbances, such as clear-cutting and selective logging. But since the time and direction of these processes are difficult to steer and manage, they are often replaced by human intervention, and trees are replanted immediately after the harvest. This is called 'reforestation'. When a forest is re-established after a long period of other land uses, such as crop production or cattle ranching, it is called 'afforestation'.

Box 6.8: Pioneer and Climax Tree Species

Two major strategies of tree regeneration can be distinguished: pioneer species, e.g. birches (*Betula* spp.), are adapted to establish on open, often disturbed sites. They require full sun and are generally fast growing and thus especially suitable for the establishment of plantations. They produce huge quantities of volatile seeds (wind dispersal) that establish particularly well on mineral soils. Climax tree species are adapted to regenerate in the microclimate conditions of already existing forests. They are shade-tolerant in their youth, but rather slow growing and much more sensitive to climate extremes (drought, frost). They usually produce far less but larger seeds. They can regenerate under old pioneer species or in gaps in old forests. Typical examples are beech (*Fagus* spp.) and firs (*Abies* spp.).

Artificial regeneration can be practised either with 'native' or 'exotic' species. Exotic species are those that are not native to the region or country. Thus, a native species in one country can become an exotic species in a neighbouring country and vice versa (cf. teak originating from Indo-Burma and nowadays being also planted in Central America, Eucalyptus from Australia planted in Spain, Monterey pine from California planted in New Zealand). The use of exotic species in forestry is often controversially and highly emotionally discussed, in contrast to agriculture, where it is not challenged that actually all commercial crops are exotics. In Germany, there is the interesting case of the Douglas fir (*Pseudotsuga menziesii*), a tree species of high economic value, that originates from western North America. Douglas fir was native to Central Europe before the ice ages, which caused the extinction of many tree taxa in Europe which can nowadays still be found in North America. Douglas fir was successfully reintroduced to Germany at the beginning of the nineteenth century and became an important source of construction timber. It established well in the forest community and can now be classified as naturalized. It is often used to replace Scots pine (*Pinus sylvestris*), which was planted to restore degraded soils in the past, since it is much more productive. Thus, Scots pine is 'native' to Germany but never occurred naturally at the majority of sites it can be found today. Originally, these sites were occupied by broadleaf trees (especially oaks). Therefore, neither Douglas fir nor Scots pine is autochthonous (native) to these sites, and it is debatable whether, ecologically, Douglas fir is worse than Scots pine.

6.2.3 Forest Services and Functions

Forests have accompanied human development from time immemorial. They provided shelter, wood for fire, tools and construction purposes, as well as fruits, mushrooms and meat. And this has not really changed to the present day. But what has changed is the intensity of usage, the sophistication of products manufacture and the improved understanding and greater importance of forests for human wellbeing. Forests have played a special role in the development of mankind due to a complex set of societal perceptions and expectations (cf. Harrison 1992). Nowadays, in addition to the sustainable production of physical goods, forests are expected to provide a multitude of services. This has resulted in restrictions in management practices that far exceed those of agricultural production, including tree species selection, mode of management, forest protection, application of agrochemicals and even mode of harvesting. This section gives an introduction into the modern usage of forests, distinguishing between their traditional function as physical resource provider and the contemporary function of non-physical service provider.

6.2.3.1 Products from Forests

The Tree as Major Source of Forest Products
A tree is defined as an erect, lignified plant composed of three major functional units, namely, root system, trunk and crown (Fig. 6.21). Thus, it comprises a below-ground and an above-ground component, which is of importance when calculating biomass and carbon sequestration potentials. The main tree parts that are used for economic purposes are the stem and major branches. Stump and roots, minor branches and leaves usually remain in the forest to maintain organic matter and nutrient cycling, since the majority of forests are not fertilized, in contrary to forest plantations.

The root system anchors and stabilizes the tree in the soil. It ensures the provision of water and nutrients, usually supported by a symbiosis

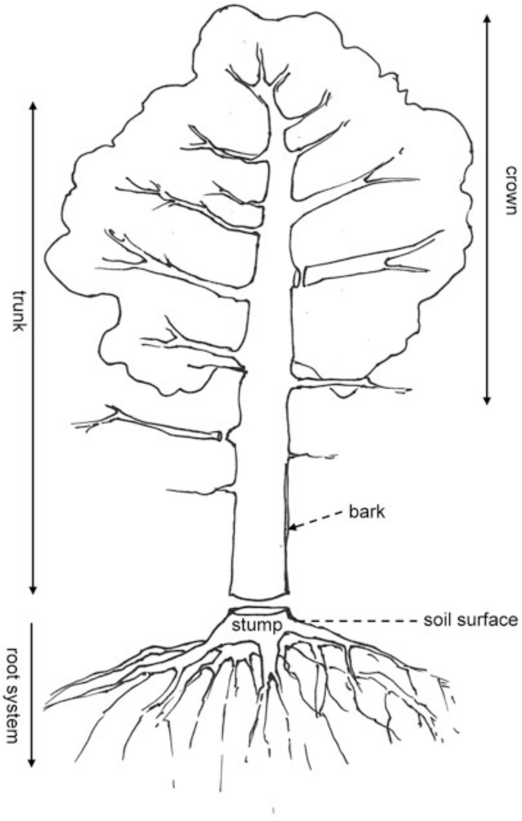

Fig. 6.21 The major components of a tree (from Young et al. 1964, simplified)

between the tree and fungi referred to as 'mycorrhiza', which is specific to the tree species. The trunk merges via branches into the crown and connects the root system with the leaves, which serve as photosynthetic units. It transports the water and nutrients absorbed by the root system in its central, woody part, the xylem, via the branches to the leaves. In return, the assimilates produced by the leaves are transported downwards in the phloem, which is located in the inner side of the bark. These assimilates are used for tree growth, including root growth and regeneration, and to provide food for the mycorrhiza. The tree crown usually begins where the trunk starts to divide into a hierarchy of branches, at the ends of which the leaves are found. This is however strongly dependent on the age and position of the tree in the population. While the crown of young trees reaches down to the soil, old trees often have a long straight bole without any branches, especially in dense forests. Solitary trees can retain their low branches throughout their entire lifespan. The tree root system needs to be flexible in order to adapt to different site conditions. Three major types of root system can be distinguished: the taproot system, heart-root system and sinker root system (Fig. 6.22).

The taproot system is based on a central, dominant root supplemented by side roots. This system provides very stable anchorage and is typical for oaks, firs and pines, but also the Neotropical rubber tree *Hevea brasiliensis*. The heart-root system does not have a clear root hierarchy, but rather spreads homogenously in the soil. It is fairly typical for a wide variety of species, such as birches and beeches. The sinker root system is characterized by a dominant horizontal root system near the soil surface from which vertical sinker roots develop that can reach considerable depths. Since the sinker roots are sensitive to waterlogged and compacted soils, they are often not well developed, erroneously leading to the perception that the root system is generally flat. Spruce trees display a typical sinker root system.

Wood

The major physical resource provided by a tree is its wood. The ability to make fire altered the course of human evolution and the energy source involved was wood. This did not change for hundreds of thousands of years, until 'recently' coal and then oil replaced wood. In the wake of the recent renewable energy boom, wood is currently experiencing a renaissance as an energy

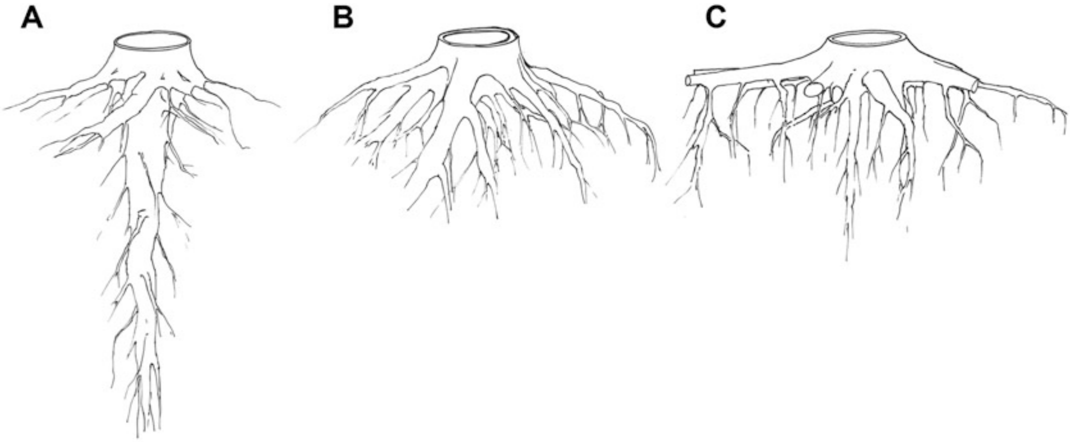

Fig. 6.22 The major root systems of trees: taproot system (left), heart-root system (middle), sinker root system (right). The actual development and structure depend strongly on site and soil conditions. Soils with a high water table can lead to a very shallow and flat root system (even in pines) © Ulrich Schmidt

source, either as raw wood or wood chips or pellets. Additionally, wood serves as raw material for tools, furniture, a wide variety of construction purposes and paper production.

Box 6.9: Chemical Composition of Wood

Carbon (50%)
Oxygen (43%)
Hydrogen (6%)
Nitrogen (1%, incl. minerals)

To understand the relevance of wood in a bioeconomy, it is crucial to be aware of its composition and features. The major components of wood are cellulose, hemicelluloses and lignin. Wood is often compared to a concrete construction, with the cellulose fibres representing the steel reinforcement which give the construction elasticity and the lignin representing the concrete which provides stability. Additionally, wood contains fat, starch and sugars as minor components, as well as resins, tannin agents, colour agents, etc. From a chemical point of view, wood is composed of carbon (C), oxygen (O), hydrogen (H), nitrogen (N) and minerals (see Box 6.9).

Since the molecular weight relation of carbon dioxide to carbon is 3.7 to 1, it is easy to calculate the carbon sequestration potential of wood from its species-specific dry weight. It should be mentioned that there is a traditional distinction between so-called hard woods (broad-leaved trees) and soft woods (conifers). Hard woods are usually heavier and have a shorter fibre length than soft woods. The latter is of importance, e.g. in paper production. Table 6.9 shows the average dry weight and bulk density of common timber species. Bulk density is the mass of dry matter in relation to the volume of the freshly harvested wood. It is an important parameter for the calculation of, among others, the carbon dioxide equivalents stored in trees. For example, a balsa tree with a volume of 1 m^3 has a dry matter wood content of about 120 kg. As the proportion of carbon is 50% (Box 6.9), this gives 60 kg carbon. The molecular weight of carbon dioxide is 3.7 times that of carbon. Thus 1 m^3 of balsa wood stores 60 kg × 3.7 = 222 kg of carbon dioxide (CO_2). The same calculation for a beech tree with a bulk density of 554 kg m^{-3} results in a figure of 1025 kg and for a pockwood tree 1935 kg.

Table 6.9 Density figures of some common tree species (all data from Knigge and Schulz 1966)

Tree species	Average dry density in g cm^{-3a}	Boundary values of dry density in g cm^{-3a}	Bulk density in kg m^{-3a}
Balsa	0.13	0.07–0.23	120.8
Spruce	0.43	0.37–0.54	377.1
Poplar	0.37	0.27–0.65	376.8
Pine	0.49	0.30–0.86	430.7
Maple	0.59	0.48–0.75	522.2
Oak	0.64	0.38–0.90	561.1
Beech	0.66	0.54–0.84	554.3
Pockwood	1.23	1.20–1.32	1045.5

[a] There is a small but relevant difference between the dry density, usually measured in g cm^{-3}, and bulk density, measured in kg m^{-3}. This is due to the fact that wood shrinks during the drying process. The bulk density relates the fresh volume of a wood sample or tree to the respective wood content. The dry density relates the volume of an oven-dried, shrunken wood sample to its weight. The latter figure is therefore higher, since the reference volume is smaller

Dry wood has a calorific value of 5–5.2 kWH kg^{-1}, and, depending on the species and its wood density, one m^3 of piled hardwood can replace around 200 l of fuel oil given a wood moisture of about 15% (air dry).

Due to its chemical and physical composition, wood has some unique features which distinguish it from other materials, resulting in a wide spectrum of applications. It is comparatively light, flexible, easy to work and often even very ornamental. It is thus used for construction purposes such as houses and boats; for flooring, furniture, carvings and tools; as well as for the production of paper and semi-natural fibres including viscose and modal. Wood also serves food industry applications, e.g. as artificial vanillin produced from lignin and as xylose, a sugar produced from wood.

Globally traded forest products are recorded in a standardized form. Table 6.10 shows the major trade categories with associated volumes for the year 2015.

Table 6.10 Global production of forest products in 2015 (FAO 2017a)

Product[a]	Unit	Production in 2015
Roundwood	million m^3	**3.714**
Wood fuel	million m^3	1.866
Industrial round wood	million m^3	1.848
Wood pellets	million tonnes	**28**
Sawnwood	million m^3	**452**
Wood-based pannels	million m^3	**399**
Veneer and plywood	million m^3	171
Particleboard and fibreboard	million m^3	228
Wood pulp	million tonnes	**176**
Other fibre pulp	million tonnes	**12**
Recovered paper	million tonnes	**225**
Paper and paperboard	million tonnes	**406**

[a] For definitions see FAO (1982, 2017b)

Other physical goods that can be obtained from forests (e.g. fruits, mushrooms) are referred to either as 'non-wood' or 'non-timber forest products' (NWFP, NTFP). Depending on the region of the globe, these may provide important contributions to the population's livelihood or be used for recreational activities. Since Mediterranean cork oak stands are classified as forests, the cork produced can also be classified as a non-wood forest product, as can the natural rubber produced in the millions of hectares of rubber tree plantations in Southeast Asia.

A special case with considerable regional importance is the meat provisioning service. So-called bushmeat is a source of protein in many African regions. In some Southeast Asian countries, e.g. Vietnam, forest species are being hunted to extinction to feed the insatiable hunger for exotic meat of the region's new rich. Bushmeat hunting and trade is usually illegal and uncontrolled and has considerable negative impacts on the affected species' populations. However, hunting practices in North America and Europe, for example, show that it is also possible to use forests as a sustainable source of considerable amounts of meat. Table 6.11 shows the case of Germany, where about 380,000 persons currently own a hunting licence.

Table 6.11 Bushmeat provision of forests and agricultural land together[a] in Germany, hunting year 2015/2016 (only hoofed game) (DJV 2017)

	Amount in tonnes[b]	Value in mio €[c]
Red deer	4865.51	21.9
Fallow deer	2157.33	10.8
Wild boar	23,908.82	95.6
Roe deer	12,330.29	61.7
Total	43,261.95	190.0[d]

[a] Hunting districts are not delimited along land-use boarders but are based on ownership. The overall hunting area in Germany amounts to 32 mio. hectares

[b] Animal with skin

[c] Price for whole animal with skin and bones ('primary value')

[d] The monetary value given in the table does not take into account the associated value chain and added values due to processing

In addition to the monetary value of the meat, annual hunting fees can also constitute a considerable source of income for forest owners and often exceed the annual income from wood production. Expenditure on hunting equipment is another economically relevant factor.

6.2.3.2 The Protective Role of Forests

Forests fulfil important protective functions. In mountainous regions, they protect settlements, farms and infrastructure from avalanches and rockfalls. Due to the specific forest climate, which maintains soil humidity and thus enhances water infiltration rates, forests usually reduce surface runoff and erosion. The root network stabilizes the soil and acts as a buffer against landslides.

Along streams, forests stabilize river banks and often serve as water (and sediment) retention areas during periods of flooding. In the tropics, mangroves have a protective role on shorelines, serving as wave breaks and also as spawning ground for fish, safeguarding the livelihood of fishermen.

Forests are also crucial for the hydrological cycle and as water protection areas. In urban centres, forests play a considerable role as air filters and oxygen providers. On a global scale, forests are crucial for carbon sequestration and serve as long-term carbon sinks.

6.2.3.3 Forests for Recreational Activities

Forests are important for recreational activities. In Germany in particular, it is said that people have a very close affinity to their forests. For this reason, forests are open access, and generally people are allowed to enter without permission. Hiking, jogging, biking and mushroom collection are common recreational activities. But hunting, which is practised nationwide, should also be mentioned.

6.2.3.4 The Socio-economic Importance of Forests in a Bioeconomy: A Case Study—Germany

Germany is a highly industrialized country with a land surface of nearly 360,000 km^2, of which 32% are classified as forest. Centuries of intensive use, degradation, reforestation and afforestation mean that today the forests are mainly production forests and only parts can be defined as near-natural. Despite this intensive use and exploitation in the past, the forests have largely maintained their original level of biodiversity, with the exception of large carnivores and predators, which historically competed with humans and have been hunted to extinction. These include bear, wolf, lynx and large birds of prey, such as eagles and vultures.

Without human interference, German forests would be characterized by broadleaf trees, mainly beech. Beech-dominated forests would cover around 74% of the total forest area, followed by oak forests with 18%. Through historical developments, however, German forests are nowadays dominated more by conifers, which cover 60% of forest area, with broadleaf forests only covering 40%. One main reason for this development is that conifers are easier to propagate and establish than broadleaf trees, especially on open lands, and in the past were often the only viable option to ensure the re-establishment of forests. As a result, the currently dominant tree species are as follows: 28% spruce (*Picea abies*), 23% pine (*Pinus sylvestris*), 15% beech (*Fagus sylvatica*) and 10% oaks (*Quercus robur*/*petraea*).

Table 6.12 Forest ownership structure in Germany (from BMEL 2017)

Forest ownership	Share of forest/%
Private[a]	48
Federal states	29
Corporations	19
Federal government[b]	4
	100

[a] About 50% of private forests are smaller than 20 ha

[b] Especially military training grounds

In recent years, there has been a trend towards the return to the original site-adapted species composition, mixed stands and abandonment of clear-cuts. This has been mainly triggered or accelerated by devastating storm damage, especially—but not only—in spruce monocultures (e.g. hurricanes Vivian and Wiebke in 1990 and Lothar in 1999). To date, around 73% of German forests are classified as mixed forests, composed of different tree species.

Forest distribution and ownership within Germany varies greatly between the federal states. Rhineland-Palatinate and Hesse have the highest forest cover at 42% each, while Schleswig-Holstein has only 10%. The ownership structure is quite heterogeneous (Table 6.12) and dominated by private owners. The private sector, that is, private and corporate forests together, accounts for 67% of the total forest area and around two million owners.

Forests and their associated value chains are of considerable socio-economic importance. On average, each hectare of forest has a timber stock of 336 m^3 and an annual timber growth of around 11 m^3, resulting in an annual timber production of more than 120 million m^3. The forest sector as a whole has an annual turnover of 170 billion euros, providing nearly 1.3 million jobs (BMEL 2017).

6.2.4 Forest Management

The management of forests has some peculiarities which need to be understood to properly assess their potentials and restrictions in a bioeconomy. One major difference compared to all other biological production systems is the time horizon. In forestry, we are dealing with decades or even centuries—in contrast to the short rotation time of modern agriculture. This requires much more foresight. In agriculture, a wrong decision might result in the loss of an annual crop. In forestry, a wrong decision with regard to tree species may reveal its disastrous consequences only after some decades. For example, a single exceptional summer or winter season can ruin the entire long-term investment in one blow, which is particularly bitter in times of high interest rates. This long-term perspective together with the necessity of food production is the main reason that, in the majority of developed countries, forests have been pushed back into less productive or difficult-to-manage sites and replaced by agriculture on good soils.

As a consequence, forest investments focus on short rotation plantations, while the management of natural or near-natural forests is practised in state-owned or traditionally privately owned forests.

6.2.4.1 The Exploitation and Use of Forests

The first use of forests was exploitative—the desired products (meat, wood, other non-wood products) were harvested without considering their regeneration. Soon, people discovered that an overuse can result in a shortage of supply. For this reason, the majority of rural tribes around the world have use restrictions, even though these may not be written down or documented as they would in a modern society.

However, forests were often cleared to create open space for crop production. This form of agriculture can still be found in the tropics, where it is called ‘shifting cultivation’ or ‘swidden agriculture’. The use of fire is a key element in this practice, and, in the course of time, vast areas can be deforested, even with very primitive tools. The forest is cut down during the dry season and the dry matter burned at the beginning of the rainy season. The open land is used for crop production for 2–3 years. After that time, it is abandoned, and the forest can re-establish and regenerate into a secondary forest.

The great onslaught on tropical forests in particular, but also boreal forests, stems from technical developments, especially the chain saw and related heavy machinery such as bulldozers, skidders and nowadays harvesters. With these tools, it was and still is possible to extract timber at an unprecedented speed. Although usually only the most valuable trees are harvested, the damage to the remaining forest can be tremendous, due to the heavy machinery and the lack of technical (felling) skills. In addition, lack of regulations and non-implementation of existing rules and corruption have led to the degradation and disappearance of large tracts of tropical forests.

In sustainable forestry, two major approaches can be distinguished: *clear felling* and *selective logging*, i.e. the targeted removal of single trees.

Clear felling is the most simple and straightforward practice. All trees on a given area are harvested. This has considerable advantages from a production point of view. First, harvesting can be conducted very efficiently, and a huge amount of biomass can be made available. Clear felling allows site modifications such as stump extraction and ploughing which requires large machinery, but also facilitates artificial regeneration. This type of forest usage and regeneration is typical in plantation forestry (cf. *Eucalyptus*, *Acacia*, *Pinus* spp.), where the fast production of a single commodity is the main objective.

Selective logging targets individual trees of high value, with the intention of maintaining forest structure and functions. It is often practised in mixed, near-natural forests. One selection criterion is a preset minimum diameter. This management practice is highly demanding and involves all aspects of management. First of all, the identification of the right trees requires the forest manager to know his forests very well. Harvesting logistics need to be worked out before logging begins to reduce the impact on the remaining forest stand. This requires the establishment of a skidding infrastructure and related felling schemes (cf. directed felling).

Fig. 6.23 Clear-felling system in conifer forests of the western USA (Photo: G. Langenberger)

Good logging skills are necessary to implement the felling scheme and minimize felling damages. The concept as a whole aims at the production of single but high-value trees. This kind of logging is usually accompanied by natural regeneration.

However, in practice, the situation is much more complex and diverse than described above, and the two approaches are often mixed, depending on local circumstances. Thus, small clear-cuts can be used to promote light-demanding species, and the natural regeneration is sometimes assisted by artificial planting either to support stagnant regeneration or to change species composition. Figure 6.23 shows the common clear-felling practice of conifer forests in the western USA. Large tracts of forests are clear-cut, but blocks of forest are maintained in between as a source of seeds.

6.2.4.2 Management Cycles

Generally, five natural development phases can be distinguished in the lifetime of a tree:

- Establishment phase: This comprises the establishment of a tree seed at a given site.
- Youth phase: The time between the establishment and maturity (seed production) of a tree.
- Optimal phase: Adult stage with regeneration.
- Stagnation phase: Decreasing vitality.
- Natural decay: die-off and replacement.

The length of each stage is species-specific and, as a result, different species are used in different management schemes. For all production forests, the stagnation phase and natural decay are eliminated by prior harvest.

Two major tree types can be distinguished based on their life strategy: the *pioneer species* and the *late-successional* and *climax forest* species (see Box 6.8). Typical *pioneer species*, e.g. birch and pine, all share a similar strategy. They produce large quantities of wind-dispersed seeds, prefer mineral soils for regeneration and require full sunlight to establish and grow. Plantation forestry uses species from this group, as they show tremendous growth in their youth but soon reach a culmination in increment, allowing for short rotations. Their natural lifespan is comparatively low (Table 6.13).

The majority of *late-successional and climax forest species* are adapted to regeneration inside the forest, in shady conditions or small light gaps. The seeds are usually larger (e.g. beech) than those of pioneers, and the seedlings can often not tolerate full sunlight exposure or temperature

Table 6.13 Life expectancy of selected tree species and production figures[a]

Tree species	Potential max. age in years	Rotation period in years	Average annual increment[b] in m^3/ha
Broadleaf trees			
Alder (*Alnus glutinosa*)	150	90	4.5–8
Ash (*Fraxinus excelsior*)	200	120	4.5–6.1
Beech (*Fagus sylvatica*)	300	150	4.2–8.6
Birch (*Betula pendula*)	120	80	3.6–4.9
Eucalyptus (*E. camaldulensis*) (plantation)	1000	7–15	2–30
Oaks (*Quercus petraea*, robur)	800	200	3.6–6.4
Teak (*Tectona grandis*)	>200	80	0.6–14.8
Conifers			
Douglas fir (*Pseudotsuga menziesii*)	1000	100	9.4–17.1
Fir (*Abies alba*)	500	150	7–12.8
Larch (*Larix decidua*)	500	140	4.1–7.2
Pine (*Pinus sylvestris*)	600	140	1.2–7.0
Spruce (*Picea abies*)	600	120	5.6–11.9

[a] Different sources: Schütt et al. (1992), Schober (1987), Lamprecht (1989), Jacobs (1955)

[b] The annual increment strongly depends on site quality and thinning concept; the values given for temperate-zone species refer to the highest rotation length given in yield tables. If rotation length is reduced, average annual increments can be higher

extremes. The establishment of these species in open spaces poses considerable problems. Therefore, such species are more often used in permanent mixed forests. They usually have slower growth in their youth than pioneer species, but maintain a considerable level of increment up to a high age and can grow quite old (Table 6.13).

Once trees have been established, either as a monoculture or within the framework of a natural regeneration concept, they need to be tended. Fertilization is common practice in forest plantations. The risk of fire should be taken into consideration in plantation schemes, but also competition from grass, which can make weeding necessary. Lianas are often reported as a serious problem hampering natural regeneration in selectively logged forests (especially in the tropics). Here, growth regulation and competition control is necessary after the establishment of the young trees, for example, misshapen and damaged trees, and trees of low vitality are removed. As the trees grow taller and start to differentiate, thinning is required, that is, the promotion of trees which fulfil quality and growth expectations by the removal of competitors. This is the first management step which can lead to positive economic returns through the marketing of wood. Depending on the management scheme, several thinning rounds need to take place before final harvest.

6.2.4.3 Forest Certification and Sustainability Initiatives

Sustainability has recently become a buzzword with as many meanings as it has advocates. The ‘invention’ of the term by Carlowitz in 1713 originally aimed at the provision of a permanent timber source for industry. Since then, the meaning of the term has evolved, based on scientific progress and ecological understanding, and has now taken on an ecosystem-oriented connotation, comprising the protection of species diversity and ecosystem functions. While forest management regulations in the temperate-zone and industrialized countries are usually well developed and implemented, forest use in the tropics has been and often still is pure exploitation, leading to forest degradation and finally transformation, sometimes intentionally to expand agricultural land. As a reaction to the tremendous forest losses in the tropics in the second half of the last century, environmentalists and other civil society organizations came together to consider options to change this development using market pressure. As a result, forest certification schemes were developed, probably the most prominent being the 'Forest Stewardship Council', better known as FSC (https://ic.fsc.org/en). As FSC was initiated by environmental and human rights organizations (in particular WWF, Greenpeace, etc.), forest owners and the forest industry reacted by creating their own, more user-friendly certification scheme, the 'Programme for the Endorsement of Forest Certification' (PEFC: https://pefc.org/). There are other certification schemes, each with somewhat different criteria and focus, e.g. that of the organic farming label 'Naturland' (http://www.naturland.de/en/).

Review Questions

- What are the specific features of forests?
- Distinguish between the different forest types.
- How do they contribute to mankind's needs and to the bioeconomy?
- What is the relevance of forests in meeting global challenges such as the mitigation of climate change?
- What is sustainable forest management?

6.3 Aquatic Animal Production

Johannes Pucher

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Abstract Aquatic animals are fundamental to a well-balanced, healthy human diet due to their profile and content of essential amino acids, polyunsaturated fatty acids, vitamins and minerals. Since the 1990s, the growing demand for aquatic food cannot be satisfied by capture fisheries alone and has therefore caused a steady increase in aquaculture production of on average 8.8% annually. Today aquaculture is the fastest-growing agricultural sector globally, especially in Asia. There are 18.7 million fish farmers globally, and annual aquaculture production is worth around 150 billion euros. It is expected that aquaculture will increasingly contribute to protein supply and healthy nutrition of the growing world population.

Fish production can be performed at different intensity levels, from production systems based on natural feed resources to closed systems in ponds or tanks which fully rely on external feed. New integrated aquaculture systems are increasingly being developed and applied, which follow a more direct implementation of a circular bioeconomy and focus on a more efficient use of nutrients and water. The best choice of production method largely depends on local conditions.

Keywords Aquaculture production; Aquaculture systems; Integrated aquaculture

Learning Objectives
After studying this chapter, you should:

- Have gained an overview of the global supply with aquatic animal biomass by fisheries and aquaculture

- Be able to explain why different aquaculture production systems and intensities are adopted in different regions and environmental surroundings
- Understand the interdisciplinary dimension of aquaculture production
- Have become acquainted with challenges for future development of sustainable aquaculture production

Aquatic animals like fish, crustaceans, molluscs and echinoderms are fundamental to a well-balanced, healthy diet due to their profile and content of essential amino acids, polyunsaturated fatty acids (e.g. eicosapentaenoic acid and docosahexaenoic acid), vitamins, and minerals (FAO 2014). On one hand, aquatic food products are increasingly consumed as healthy and easily digestible food by richer consumers. On the other hand, aquatic animal-based protein resources are highly important for the food and nutrition security of the poor in developing countries and emerging economies.

In 2012, the global production of aquatic animal-based biomass reached 158 million tons, of which 136.2 million tons were used for human consumption and 21.7 million tons for other uses like fishmeal and fish oil production (FAO 2014). The growth in world population, rising per capita consumption, and better access to global and local markets have led to an increasing global demand for aquatic food and feed resources (FAO 2014). The World Bank (2013) expects the demand to increase aquatic food production up to 152 million tons by 2030.

Of the 2012 total annual production, 91.3 million tons were harvested by capture fisheries, and 66.6 million tons were produced in aquaculture (Fig. 6.24). For human food production, capture fisheries mainly supply the markets with organisms of higher trophic levels, like piscivorous or carnivorous fish, mollusc species and crustaceans (Neori and Nobre 2012; Tacon et al. 2010). Species of lower trophic level (esp. pelagic fish species) are also used for non-food purposes including the production of fishmeal and fish oil, which are dominantly used as feed sources in aquaculture (Shepherd and Jackson 2013). Capture landings for food and non-food purposes are dominantly harvested in seas and oceans (79.7 million tons in 2012), whereas 11.6 million tons were landed from freshwater systems.

Over the past decade, the amount of aquatic animal biomass landed globally by capture fisheries has been maintained at a relatively constant level through the utilization of ever more effective fishing gear and landing technologies and by the overexploitation of several natural stocks (Pauly 2009). Since the 1990s, the growing demand for aquatic food cannot be satisfied by capture fisheries alone and has caused a steady increase in aquaculture production of on average 8.8% annually, making aquaculture the fastest-

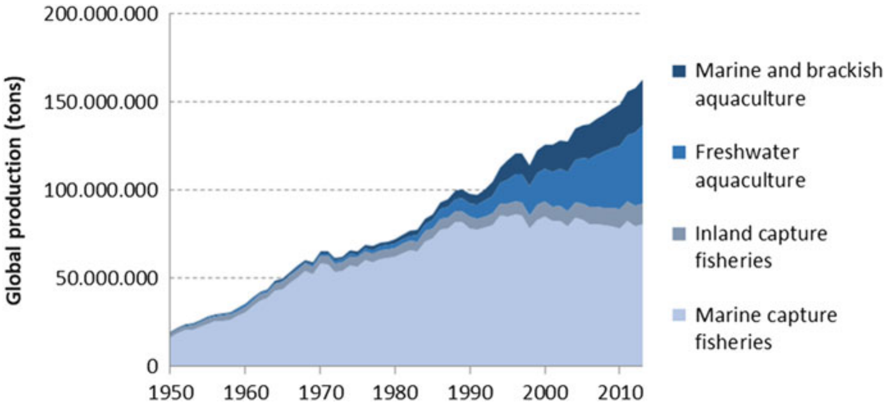


Fig. 6.24 World capture fisheries and aquaculture production (data from FAO 2015a, b)

Table 6.14 Aquaculture production by region in 2012 (FAO 2015a, b)

	Production of aquatic animals (million tons)
Africa	1.49
Americas	3.19
Asia (excl. China)	17.79
China	41.11
Europe	2.88
Oceania	0.18
Total	66.63

growing agricultural sector globally (FAO 2014), especially in Asia (Table 6.14). According to the FAO (2016), there are now 18.7 million fish farmers worldwide, and aquaculture production is worth around 139 billion euro (83 billion euro from finfish, 16 billion euro from molluscs, 30 billion euro from crustaceans, 3 billion euro from other aquatic animals and 5 billion euro from seaweeds). Aquacultural production is growing in developing and emerging economies in particular, leading to a strong global imbalance in geographical supply and demand in seafood, as 37% of seafood produced globally is exported (data 2012, FAO 2014). In 2012, 49% of the seafood import value of developed countries originated from developing countries (FAO 2014). Consequently, seafood products consumed in industrialized countries are often produced in developing or emerging economies. This makes harmonized and internationally accepted standards and regulations for production, processing and trading of aquatic foods essential to ensure an adequate level of protection for the consumer.

Aquaculture is defined by the FAO as having '. . .some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, . . .' (FAO 1997, p. 6). Today, about 520 single species or groups of species (excluding plants and mammals) are cultured in marine, brackish, or freshwater aquaculture systems. As there is a large variation in the nutritional requirements and feeding behaviour (planktivorous, herbivorous, detritivorous, omnivorous, piscivorous/carnivorous) of cultured species, a wide range of aquaculture production systems exist to accommodate the specific needs of the species and integrate aquaculture into the local/regional conditions. Aquaculture production systems differ greatly with regard to their intensity of production, which can be classified (Fig. 6.24) according to the yield, stocking density, level of external feed/fertilizer inputs, dependency on natural food resources, management/technical requirements, capital, labour and risks (Edwards et al. 1988; Tacon 1988; Prein 2002). In general, aquaculture production systems are classified into three intensities (extensive, semi-intensive and intensive aquaculture) and are integrated differently into the spatial bioeconomies and biomass flows.

Feed Conversion Ratio (FCR)

The FCR indicates how much feed (dry matter) is needed to produce one unit of fresh fish. This unit highly depends on the feed quality, culture condition, production intensity and trophic level of the species.

In *extensive aquaculture*, aquatic organisms from mainly lower trophic levels are grown solely on natural feed resources (e.g. bacteria, phytoplankton, zooplankton, zoobenthos, detritus, prey fish) without substantial inputs of external feed or fertilizer. The systems are most often run as *polycultures* (combination of several species with different feeding niches in the same pond) for local and regional markets. The stocking densities per area and the annual yields are low due to the limited productivity of the natural feed resources. Extensive aquacultures require only low levels of technical equipment, management schemes and financial investment, but large areas of water per yield, as the internal production of feed resources is entirely based on natural primary (algae) production within the ponds. Extensive aquaculture systems are only applicable in areas where suitable surface waters are abundant and are not polluted. These natural aquaculture systems are often highly important for the preservation of biological biodiversity as they provide suitable habitats for a wide range of

Fig. 6.25 Semi-intensive carp polyculture in a pond in Vietnam (Photo: J. Pucher)

flora and fauna. As no external feed and fertilizers are used, extensive aquaculture systems act as a nutrient sink and counteract eutrophication. In developing countries in particular, extensive aquaculture plays an important role for the food security of poorer communities, as minimal management and inputs are required to produce highly nutritious food resources. The future expansion of extensive freshwater aquaculture systems is very limited due to the limited availability of suitable water resources. It would require the more efficient use (intensification) and recycling/multiple use of freshwater in integrated systems without increasing the risk of contamination with undesired substances that reduce the safety of food products. A special form of extensive aquaculture is *extractive aquaculture* in which filter-feeding aquatic species are cultured in more eutrophic waters. The most predominant example is the production of bivalves (e.g. mussels, oysters) which are grown in coastal waters and feed on plankton and detritus. Similarly, seaweeds are grown in coastal waters and take up dissolved nutrients. These extractive aquacultures have high potential as they counteract eutrophication especially in coastal zones, but care should be taken regarding potential contamination with marine toxins, pathogens and undesired substances that are harmful for human health.

In *semi-intensive aquaculture*, aquatic organisms are grown in natural or constructed ponds (Fig. 6.25) on a combination of external supplemental feed and natural feed resources supported by organic or inorganic fertilizer inputs in combination with a suitable water management. Again, these systems are most often run as *polycultures* of several species of lower trophic levels for regional or national markets. To effectively utilize the protein-rich natural feed resources, external feeds often contain high levels of carbohydrates/energy to supply the cultured species with the required nutrients in a balanced and effective way (De Silva 1995). In developing countries, by-products of lower quality (e.g. press cakes, brans and manure) are often used as feed and fertilizer resources. Semi-intensive aquaculture is characterized by medium stocking densities, moderate use of technical equipment (e.g. aeration) and medium management requirements. As with extensive aquaculture, semi-intensive aquaculture offers a range of habitats for flora and fauna and stabilizes biodiversity. On a global scale, semi-intensive aquaculture is extremely important for the supply of highly nutritional food and is most often highly integrated into spatial bioeconomies and biomass flows (e.g. water, feed and fertilizers). In the developing countries and emerging economies of Asia and Africa, semi-intensive aquaculture in integrated agriculture aquaculture (IAA) systems is very important. These systems integrate agricultural production with livestock husbandry and pond aquaculture. By-products from each farming activity are used as feed or fertilizer for another farming activity, leading to a circular bioeconomy at farm or regional level. However, in such IAAs, an intensification of one farming activity (e.g. application of pesticides or inorganic fertilizers) has a direct impact on the efficiency of the entire system and may also affect the safety of their products (Pucher et al. 2014; Schlechtriem et al. 2016). A sustainable and safe expansion of this type of aquaculture needs to be well integrated into the regional situation. But the largest part of an increased future production necessary to supply the rising demand can only be achieved by an intensification of aquaculture (Tacon et al. 2010).

Intensive aquaculture is the production of aquatic species, mostly piscivorous/carnivorous species, in monocultures for large national/international markets. It enables the highest control over the culture conditions including water quality, feed utilization, hygienic conditions and health management. In intensive aquaculture, the cultured species are grown solely on external feeds, which are specifically formulated and produced to supply them with all required nutrients and energy, thus enabling an efficient and maximized utilization of resources such as water and feeds. These systems are specifically designed to adjust and stabilize the culture conditions to the needs and requirements of the cultured species (e.g. oxygen supply, temperature, currents, salinity, pH). The use of technical equipment (aerators, water quality monitoring, filters, nitrification and denitrification units, pumps, disinfection units, temperature controls, automatic feeders, etc.) permits the highest stocking densities. This high-intensity aquaculture allows the greatest yields, space efficiency, monetary return and standardization of products, but necessitates a high level of monetary investment, management and skilled staff (Fig. 6.26). Potential risks are insufficient quality and safety of feeds and water resources, environmental pollution and eutrophication by effluents, genetic mixing of aquaculture escapees and wild stocks, inadequate utilization of veterinary medicines (e.g. antibiotics) and production technologies, as well as outbreaks of diseases, technical failure and price competition on national/international trading.

Intensive aquaculture is conducted either in net cages (Fig. 6.27) or in land-based flow-through systems or closed recirculation aquaculture systems (RAS). Net cages are installed in rivers, lakes or marine waters and enable direct contact of the cultured species with the surrounding environment via the water, which supplies them with oxygen and flushes out faeces and dissolved metabolites. This type of aquaculture is affected by the surrounding environment through diseases and parasites, which may attack the cultured species, and also directly affects the environment through the effluent water, which makes the site selection of such production highly important.

Flow-through systems and closed recirculation aquaculture systems (RAS) are constructed indoor or outdoor tanks and ponds (Figs. 6.28 and 6.29). In so-called land-based systems, the water flow can be better controlled, allowing higher protection of cultured species from external influences (e.g. parasites, contaminated waters) and also higher protection of the environment, as effluents can be filtered and treated before release. Flow-through systems direct water through the culture raceways, supplying oxygen to the organisms and flushing out metabolites and faeces. By contrast, RAS recycle the water by filtering solid wastes out and oxidizing the highly toxic ammonium (main metabolite of the culture species' protein metabolism) to less toxic nitrate. The reaction allows multiple recirculation of the water and thus a higher water-use efficiency. Inclusion of denitrification units can even increase this multiple water use, allowing highly

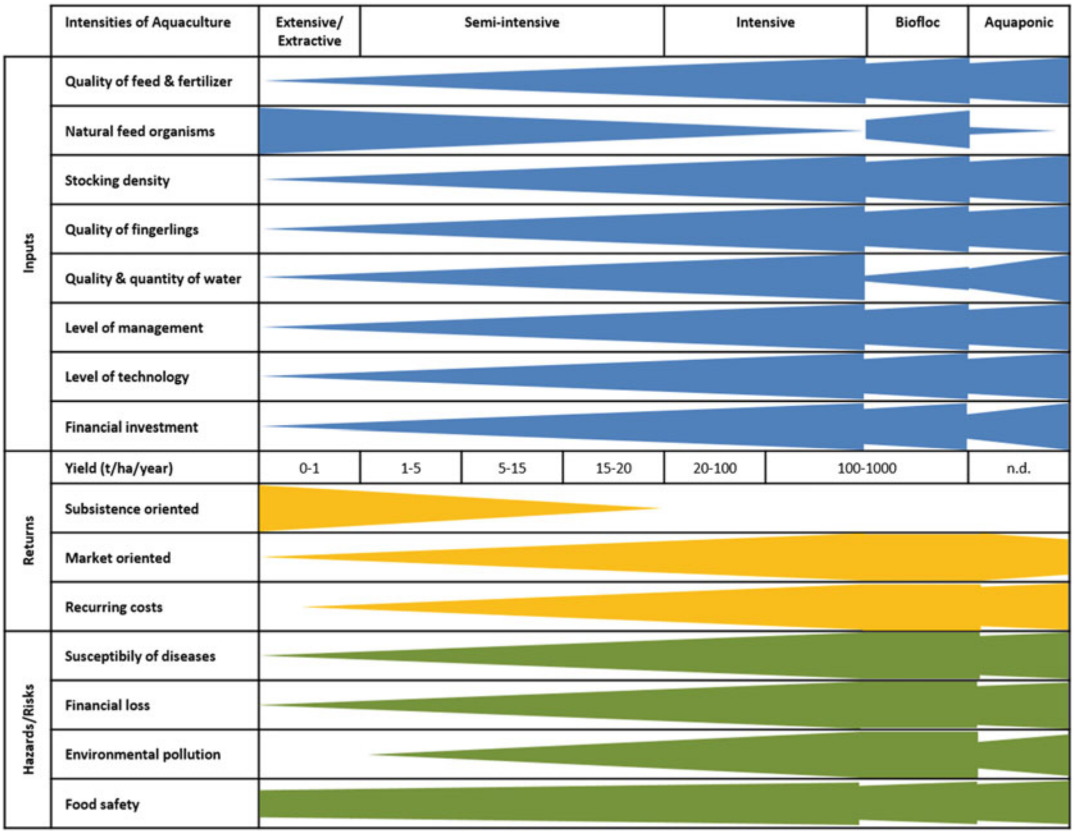


Fig. 6.26 Classification of different aquaculture production systems according to their intensities of inputs, returns and hazards/risks (redrawn and expanded from Edwards et al. 1988 in cooperation with U. Focken)

Fig. 6.27 Intensive net cage culture of salmon in Norway (Photo: J. Pucher)

Fig. 6.29 Intensive outdoor shrimp production in a pond system in Vietnam (Photo: J. Pucher)

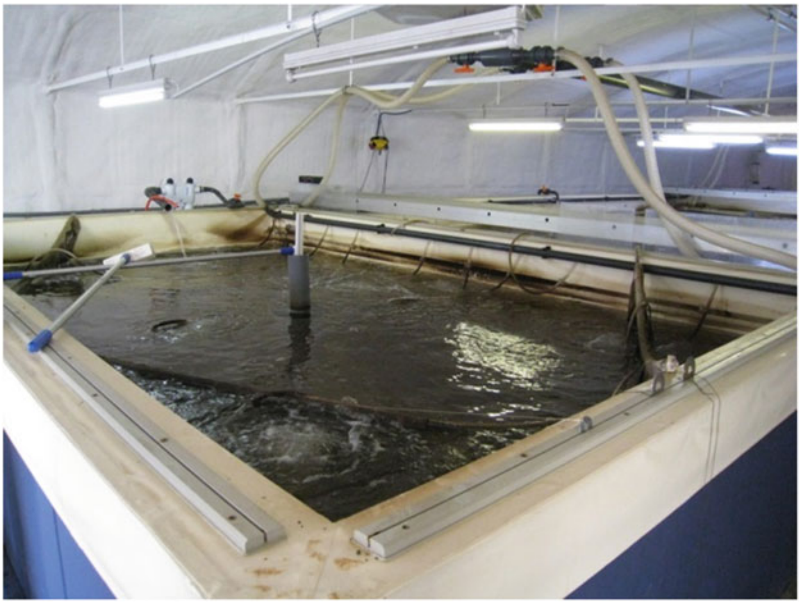


Fig. 6.28 Intensive indoor shrimp production in a recirculating aquaculture system in Germany (Photo: J. Pucher)

controlled production with minimal use of water resources (Fig. 6.30).

> **Fish-In-Fish-Out (FIFO) Ratio**
> Measure to compare the dependency of different aquaculture species on marine feed resources (fishmeal and fish oil) from wild non-food-producing fish. This concept of indexing is highly discussed (Kaushik and Troell 2010; Byelashov and Griffin 2014).

Intensive aquaculture offers great potential for future production due to its high productivity, efficiency and controllability. But an increase in intensive aquaculture production is creating a higher demand for classical feed resources (e.g. fishmeal and fish oil) and land/water to

Fig. 6.30 Intensive outdoor pangasius production in a pond system with feed supply in Vietnam (Photo: J. Pucher)

produce plant-based feed resources (Tacon and Metian 2008). The limited availability and increasing price of fishmeal and fish oil for the intensive production of piscivorous species and increasing consumer awareness are pushing the sector to minimize the use of fishmeal/fish oil and replace them with alternative, plant-based resources. Nowadays, soybean protein in particular is often used in aquafeeds for piscivorous species. However, globally other plant-based as well as animal-based by-products from other branches of the bioeconomy are also used (Hardy 2010; Hernández et al. 2010), including press cakes and protein extracts from plant oil production, protein extracts from single-cell technology, blood and bone meal, insect meal and unsaturated fatty acids from vegetable and algae oils.

Other novel methods of integrated aquaculture systems are increasingly being developed and applied, which follow a more direct implementation of a circular bioeconomy and focus on a more efficient use of nutrients and water. Integrated multi-trophic aquaculture (IMTA) is a combination of several aquatic species of different trophic levels which are co-produced in order to utilize the applied nutrients more effectively and reduce environmental impacts. A prominent example is the combination of intensively fed carnivorous fish with filtering species such as mussels or seaweed. This might be realized in open waters, or shellfish is farmed in fish farm drainage canals, while the effluents from the fish are directed over mussel and/or seaweed beds. These filtering species filter out solid particles and algae that take up dissolved nutrients from aquaculture effluents. This concept allows the partial binding of emitted nutrients from intensive aquaculture to supply additional products (e.g. mussels, seaweed).

Another form of modern integrated aquaculture is the combination of intensive aquaculture (of fish) and hydroponic production of plants like herbs and vegetables. These so-called aquaponic systems are designed to utilize the excreted dissolved nutrients from aquaculture production as fertilizer for plants. Some systems even recycle water from evapotranspiration. This increases both nutrient and water-use efficiency. These systems are currently being promoted for (peri-) urban regions to supply urban niche markets with locally produced food products. Additionally, waste heat from industrial activities can be utilized to increase their competitiveness. However, the competitiveness and efficiency of aquaponic production systems is presently the subject of scientific discussion.

Biofloc systems are increasingly applied and are a mixed form of semi-intensive and intensive aquaculture. Here, fish or shrimps are kept in intensively managed aquaculture tanks or ponds with minimized water exchange. In addition to the feed for the cultured species, low-value, carbohydrate-rich by-products (e.g. molasses, vinasses) are applied as an energy source for a microbial community of heterotrophic and chemotrophic bacteria. These bacteria organically bind the nutrients excreted by the culture species (e.g. nitrogen and phosphorus) to form so-called bioflocs, which are eaten by the culture species. High water aeration is necessary to supply the culture species and bacterial community with sufficient oxygen and keep the bioflocs suspended in the water so that dissolved nutrients are efficiently captured and serve as an internally recycled feed resource. Such systems promise a higher-nutrient efficiency and productivity of used water sources, but potential risks include the accumulation of undesirable substances in the system.

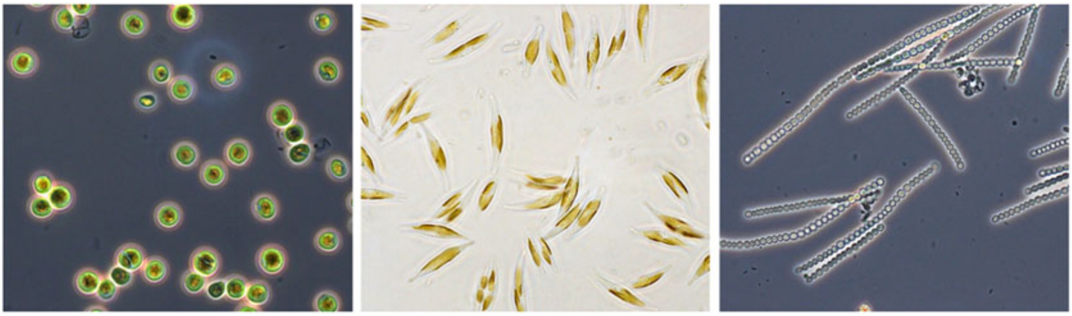
As described above, aquaculture can take a number of different forms and operate at various scales, while it can vary from subsistence-oriented small-scale fish farming in the family pond to the industrial-scale production for international markets. Aquaculture is part of complex value chains and is influenced by a range of environmental, societal and governmental factors. For future aquaculture production of healthy and safe food products, it is important to focus on environmental, social and economic sustainability and integrate aquaculture into the regional surrounding circumstances. These surrounding circumstances include the availability and quality of water resources, feed resources, know-how of workers and public, availability of technology, acceptance within the society for the production systems and products, permitting regulatory framework on environmental performance, production licences, water use, animal welfare, market demand and prizes, production costs, seasonality, risks of food safety and biosecurity, availability and quality of stocking material, climate change and post-harvesting/processing. Risk assessments, value chain analysis and market surveys might be needed to mitigate potential risks. In general, it is more resource efficient to culture species of lower trophic level and increase the utilization of by-products by establishing production chains with alternative feed resources. The choice of production method is highly dependent on local conditions, and therefore, it might be suitable to establish polycultures/multi-trophic systems in one location but more suitable to establish intensive recirculating aquaculture systems (Fig. 6.28) in another location. Improving animal welfare and sustainability of aquaculture as well as implementing eco/welfare-labelling and quality assurance/certification is targeted to increase the consumer acceptance.

Review Questions

- Which of the various aquaculture production systems show a higher productivity and economic performance?
- Which of the various aquaculture production systems are more sustainable in terms of the use of water, feed resources and energy in a site-specific context?
- What risks might arise from circular production concepts for the cultured animals and the consumers?

6.4 Microalgae

Ursula Schließmann, Felix Derwenskus, and
Ulrike Schmid-Staiger



Light-microscope images of different microalgae species. © Fraunhofer IGB, Stuttgart

Abstract Microalgae are one of the most important global biomass producers and can be used commercially to produce specific food, feed and biochemical compounds. The cultivation process differs completely from that of land-based plants because they are grown under more or less controlled conditions in different types of bioreactor systems in salt, brackish or fresh water. Special processing requirements apply to the extraction of valuable compounds from algae biomass and further use of the residual biomass, especially in cascade utilization. In general, the chemical characteristics and market specifications, for example the required degree of product purity, determine the downstream processing technique. Additional requirements are the avoidance of an energy-intensive drying step wherever possible and the ensuring of gentle extraction processes that both maintain the functionality of biochemical compounds and permit the extraction of further cell components.

The vast number of microalgae strains differ fundamentally in cell size, cell wall formation and biomass composition. By applying successive extraction procedures, both the principal fractions (e.g. proteins, polar membrane lipids with omega-3 fatty acids, non-polar triacylglycerides) as well as high-value components such as carotenoids can be obtained sequentially from the microalgae biomass.

Keywords Microalgae cultivation; Reactor systems; Algal composition; Algae-based products; Microalgae biorefinery

Learning Objectives

After reading this chapter, you will:

- Have gained an overview of the definition, metabolism and capability of microalgae
- Know about the most important parameters for the cultivation of microalgae in different photobioreactor systems
- Be aware of the huge diversity of valuable constituents in microalgae biomass and know about their areas of application
- Understand the main difficulties in downstream processing of microalgae biomass in terms of a biorefinery concept

6.4.1 Microalgae Cultivation, Composition and Products

Microalgae are one of the most important global biomass producers. Not only do they provide a large contribution to global oxygen production, but they are also able to produce several high-value compounds such as proteins, omega-3 fatty acids or antioxidant colourants. Microalgae represent a diverse group of plant-like, unicellular organisms, of which there are an estimated 300,000 different species on earth today. So far, about 40,000 species have been described, and a few have been analysed in detail (Batista et al. 2013; Mata et al. 2010). The term 'microalgae' includes prokaryotic cyanobacteria as well as eukaryotic microalgae species capable of growing in the presence of sea water (e.g. oceans), fresh water (e.g. lakes, rivers) and on several kinds of ground surfaces (e.g. soil) (Richmond 2004).

Microalgae
The term microalgae includes prokaryotic cyanobacteria and eukaryotic microalgae species. According to recent estimations, about 300,000 different species exist on Earth today.

Depending on the species, microalgae are able to grow under heterotrophic, mixotrophic or photoautotrophic conditions (Morales-Sánchez et al. 2014; Perez-Garcia et al. 2011; Cerón-García et al. 2013) (Table 6.15). When cultivated in photoautotrophic conditions, they capture light and use its energy to convert carbon dioxide (CO_2)—a relevant greenhouse gas—via photosynthesis into chemical energy in the form of carbon-rich biomass. It is estimated that about 50% of global oxygen is produced by microalgae. Like terrestrial plants, microalgae require nitrogen and phosphorus for optimal growth. However, compared to higher plants, their cultivation has a considerable number of advantages (Schmid-Staiger et al. 2009). These include a five-to-ten times higher biomass productivity per area unit than terrestrial plants and the possibility of cultivation in controlled reactor systems on land not suitable for conventional agricultural purposes (Meiser et al. 2004). Closed reactor systems lead to a substantial reduction in water consumption compared to the cultivation of land plants, as no water is lost through evaporation or infiltration. Since several microalgae species can be cultivated in brackish or coastal seawater, the consumption of fresh water is reduced as well.

Reactor Systems

Cultivation in reactor systems enables the constituents of microalgae biomass to be influenced by regulating various process parameters, in particular nutrient supply and light intensity (Münkel et al. 2013). One major challenge in the cultivation of phototrophic organisms is the provision of sufficient light for the culture. For this reason, many different open and closed bioreactor systems have been developed for algae cultivation, each with its own advantages and disadvantages (Singh and Sharma 2012). The system used is determined by the desired product and the algae species. The most common systems are open ponds, tubular reactors and flat-panel reactors (see Fig. 6.31).

Open ponds are natural or artificial lakes with a culture depth of about 20–30 cm. In general, these reactors reflect the natural algae environment. The first open ponds were built in the 1950s, and research in this field is still continuing

Table 6.15 Potential growth conditions of different microalgae

	Heterotrophic	Mixotrophic	Photoautotrophic
Light		x	x
CO_2		x	x
Organic carbon source	x	x	

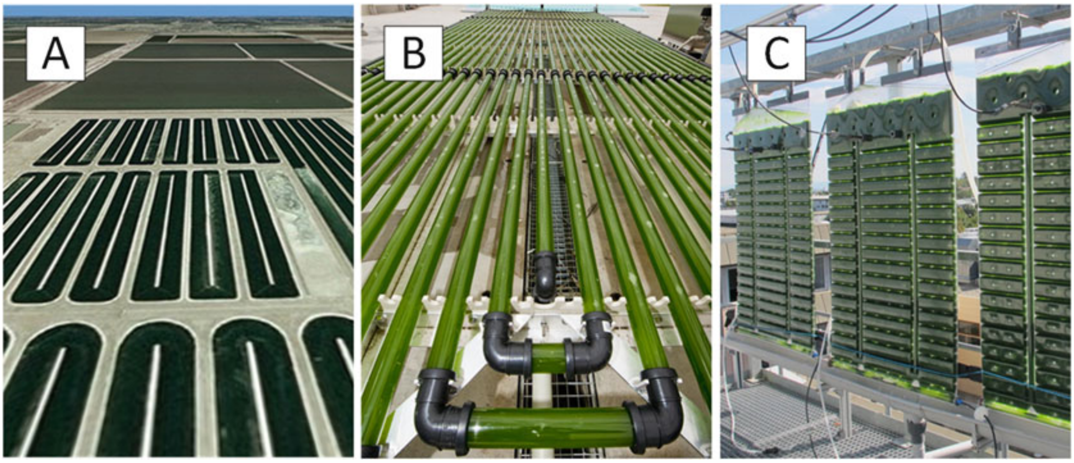


Fig. 6.31 Different bioreactor systems used for microalgae cultivation: (**A**) race-way ponds in southern California (White 2011, AlgaeIndustryMagazine.com), (**B**) tubular reactors (AlgaePARC, Wageningen University, Netherlands) and (**C**) flat-panel-airlift bioreactors (Fraunhofer IGB, Stuttgart, Germany)

today (Das et al. 2015). Raceway ponds are an improvement on simple ponds and are usually equipped with a paddle wheel to generate a higher flow velocity (see Fig. 6.31A). The cultivation of algae in open ponds is an established technology with low investment costs. Furthermore, ponds are simple to operate. Disadvantages are low process control (e.g. lack of cooling, difficult CO_2 supply, high water evaporation rate), low biomass productivity and low algae concentration (approx. 1 $g_{DW}\ L^{-1}$) due to insufficient light supply as a result of inadequate mixing conditions. The open system also carries a high risk of contamination with other algae, bacteria and predators. Open ponds are particularly used for the commercial cultivation of extremophile algae such as *Spirulina*, which tolerates high pH values, and *Dunaliella salina*, which can survive in high salt concentrations.

In *tubular reactors*, the biomass is pumped through transparent tubes with a diameter of several centimetres and a length of up to 100 m. CO_2 is usually supplied in a closed mixing tank. The CO_2 consumption and oxygen production of the microalgae can lead to pH and oxygen gradients in the culture, as the flow in the tubes is usually nonturbulent. The closed system enables high process control and low contamination risk. Examples of microalgae species grown in tubular reactors on a large scale are *Chlorella vulgaris* for food supplements and *Haematococcus pluvialis* for the production of astaxanthin, a red colourant (Pulz 2001).

As light is the most important parameter in algae cultivation, reactors with a high surface-to-volume ratio have been developed. *Flat-panel reactors* are vertical systems with a culture depth of only a few centimetres and are mixed by bubbling gas at the bottom. This gas flow prevents oxygen accumulation and the high light availability leads to an increased biomass productivity and concentration compared to other bioreactor systems. The concentration can be more than ten times higher than in open ponds. However, in conventional flat-panel reactors, there is little horizontal mixing, as the gas bubbles only move directly upwards in an unimpeded manner. For this reason, a modified flat-panel-airlift (FPA) reactor has been developed (see Fig. 6.31C). It consists of static mixers that produce a circular current in each chamber of the reactor (Bergmann et al. 2013). The flow pattern constantly entrains the algae cells from the dark to the light side of the reactor (see Fig. 6.32). Thus, an optimal light

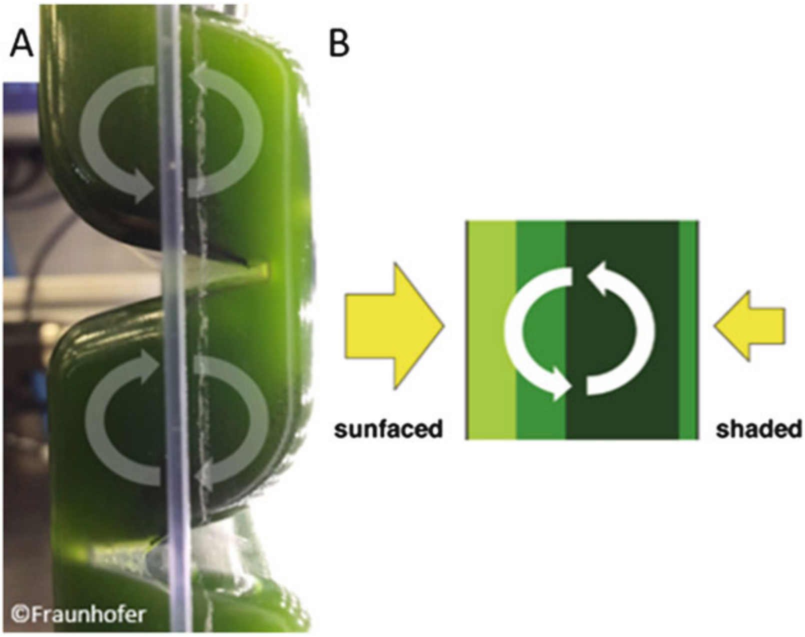


Fig. 6.32 (**A**) Side view of a flat-panel-airlift bioreactor and (**B**) schematic image of the flow pattern within each compartment. The cyclic flow pattern provides a transport from microalgae cells from the sun-faced to the shaded side of the bioreactor

Fig. 6.33 Flat-panel-airlift bioreactor (FPA) with artificial illumination, pH- as well as temperature control and automated feeding system ©Fraunhofer IGB

distribution is ensured, which results in very high productivities (up to 2 g_{DW} L^{-1} d^{-1}) and leads to a high biomass concentration of up to 20 g_{DW} L^{-1}.

These reactors can be equipped with automation systems, which provide full control of CO_2, temperature, pH value and nutrient concentration in the culture (Münkel et al. 2013). The reactors can be used indoors illuminated by LEDs (see Fig. 6.33) or outdoors operating on natural sunlight (see Fig. 6.31C).

Algal Composition and Products

Microalgae can produce a large number of substances that are of interest to various sectors

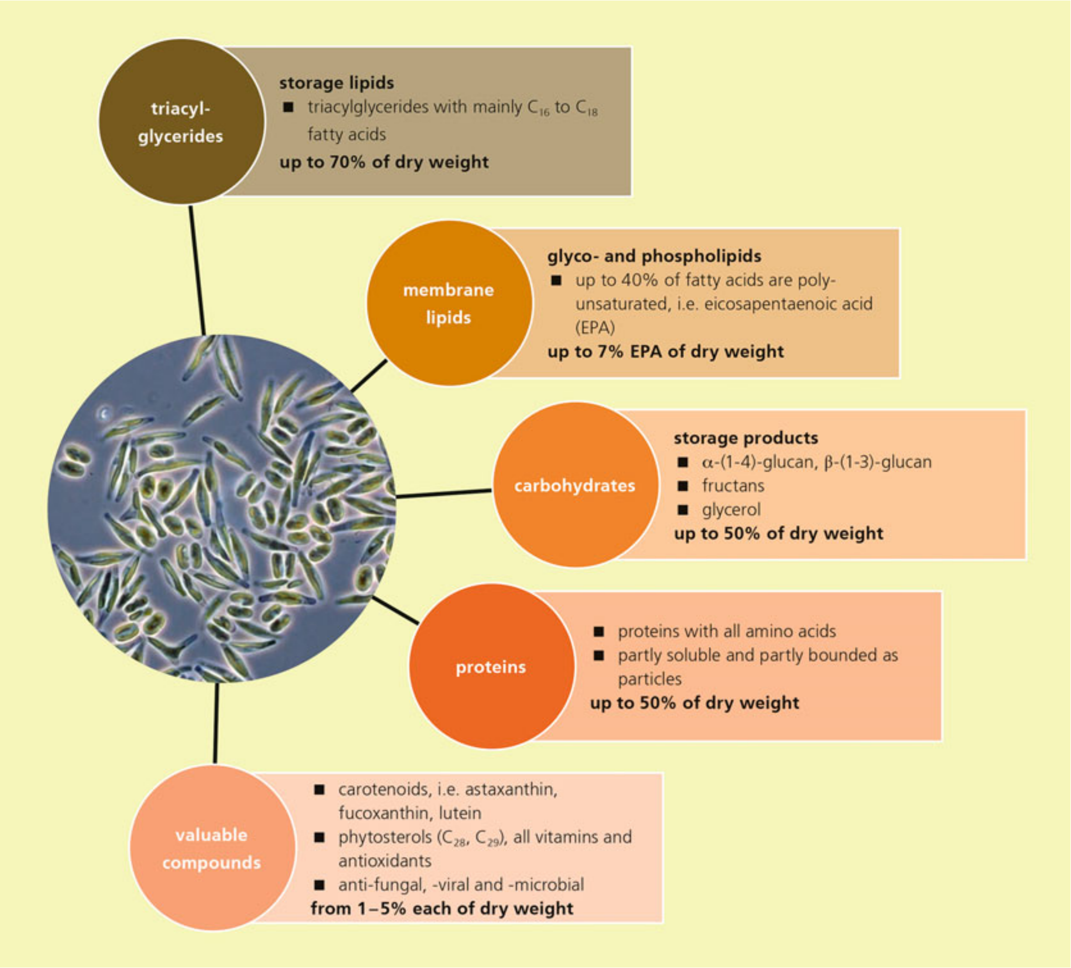


Fig. 6.34 Biochemical components of microalgae biomass. The amount of each component depends on the species as well as the cultivation conditions

including, in particular, the food, feed, cosmetics and pharmaceutical industry. Depending on the species used and the cultivation conditions, they are able to produce large quantities of fatty acids in the form of triacylglycerides (up to 70% of dry weight), proteins (up to 50% of dry weight) or polar membrane lipids with omega-3 fatty acids (up to 7% of dry weight), as well as a broad variety of carotenoids and phytosterols. The aim is to use these compounds in food production without changing their techno-functional, nutritional and physiological properties (see Fig. 6.34).

Due to the great diversity of constituents and different cell wall characteristics of various microalgae species, it is necessary to carry out selective processing of the biomass in order to effectively extract high-quality components. The composition of microalgae ingredients depends on the selected strain and the process conditions (Pal et al. 2011; Mulders et al. 2014). Given sufficient nitrogen and phosphorous supply, microalgae tend to produce large amounts of proteins. These can constitute up to 60% of the total dry cell mass and appear very suitable for food and feed purposes, since the amino acid

Table 6.16 Microalgae ingredients and their areas of application

Microalgae ingredients	Area of application
Carbohydrates	Use as renewable energy source (e.g. bioethanol, biodiesel, palm oil substitute)
Triacylglycerides	
Proteins	Supplements for food and feed applications (e.g. animal feed in aquacultures, fish oil replacement, nonanimal protein source)
Membrane lipids	
Pigments and phytosterols	High-value products for nutrition, chemical and pharma industry

profile is in balance with WHO/FAO recommendations (Becker 2007). However, the only commercial products on the market so far are dietary supplements. As chlorella is rich in chlorophyll and lutein, it is thought to have beneficial health properties and is used in supplements for the reduction of oxidative stress and treatment of several diseases including age-related macular degeneration (ARMD) (Granado et al. 2003). In addition, some microalgae species (e.g. *Phaeodactylum tricornutum*, *Pavlova lutheri*, *Nannochloropsis oceanica*) have phospho- and galactolipids in their chloroplast membranes that contain polyunsaturated omega-3 fatty acids, especially eicosapentaenoic acid (EPA, C20:5, ω3) and docosahexaenoic acid (DHA, C22:6, ω3) (Chini Zittelli et al. 1999; Krienitz and Wirth 2006; Pieber et al. 2012). EPA (typically contained in the human diet in fish oils) can act as a precursor of prostaglandin-3, which can inhibit platelet aggregation. It is also thought that a specific EPA intake can help to reduce inflammation and the symptoms of depression (Martins 2009).

When microalgae cells are cultivated under nitrogen or phosphor starvation, some species (e.g. *Chlorella vulgaris*) are able to accumulate huge amounts of triacylglycerides consisting of glycerol and saturated and mono-unsaturated lipids (mainly C16-C18 fatty acids). Under appropriate conditions, these fatty acids constitute more than 60% of the total dry mass (Münkel et al. 2013). Other species (e.g. *Chlorella sorokiniana*) are able to accumulate large amounts of carbohydrates in the form of starch. Extraction of unsaturated fatty acids and carbohydrates is simple. These products are of interest to the energy sector, since they can be converted to biodiesel (from fatty acids) or bioethanol (from carbohydrates) or used as platform chemicals for further synthesis (Harun 2010). Until now, all studies and estimations have confirmed that the production of biodiesel from microalgae is still too expensive and not yet competitive with fossil fuels (Rodolfi et al. 2009; Norsker et al. 2011). However, in addition to the main products, microalgae biomass can include several high-value by-products such as carotenoids (e.g. astaxanthin, β-carotene, fucoxanthin, lutein) and phytosterols, which are of interest considering their antioxidant and anti-inflammatory properties (Ahmed et al. 2014; Macías-Sánchez et al. 2007; Ahmed et al. 2015; Francavilla et al. 2010). Some carotenoids can be used as natural and healthy food colourants (see Table 6.16).

6.4.2 Microalgae Biorefinery: Adding Value by Fractionation

In the context of the bioeconomy, algae biomass needs to be utilized as holistically and efficiently as possible. Although microalgae can be used as whole cells for nutritional purposes, it is often worth fractionating the different constituents to add value to the biomass and thereby vindicate comparatively high production costs. However, developing appropriate downstream processes is a huge challenge, since microalgae biomass usually contains more than one main constituent of interest, e.g. saturated fatty acids as biodiesel feedstock, and proteins, omega-3 fatty acids and carotenoids for food and feed applications. Furthermore, the quality and amount of valuable components can vary greatly according to the origin of each species and cultivation conditions, e.g. light availability and nutrient supply (Münkel et al. 2013; Pal et al. 2011). Hence, cell disruption and extraction parameters have to be adjusted carefully depending on the composition of constituents and also individually for each specific microalgae strain.

Well-known downstream processes used, for example, for terrestrial plants or bacteria, cannot be easily transferred to microalgae, since these are cultivated in aqueous media and the solid matter content is far below the values achieved in classical fermentation processes (Posten and Feng Chen 2016). Thus, microalgae biomass requires a solid-liquid separation (e.g. by flotation, filtration or centrifugation) to harvest and concentrate microalgae cells produced in open ponds or closed bioreactors. Subsequently, an additional drying step (e.g. spray drying or lyophilization) can be necessary to remove residual water, since water may interfere with solvent extraction or disturb the hydrolysis process for biofuel production.

In most cases, harvesting is followed by a cell disruption step. For many microalgae species, this step is mandatory since multilayered microalgae cell walls can be very robust and might impede direct contact between the solvent and compounds to be extracted (Brennan and Owende 2010). Cell disruption can also improve the bio-accessibility of antioxidant compounds used in food and feed applications (Gille et al. 2016). For this purpose, mechanical cell disruption, e.g. by bead milling, high-pressure homogenization or sonication, tends to be more effective than chemical or enzyme-based treatments (Safi et al. 2014).

Cascaded Extraction
Combination of multiple extraction steps in order to extract multiple products while avoiding the degeneration of molecules and organic compounds within each fraction.

Nowadays, one of the most common approaches in the extraction of products from algae is to separate lipids (e.g. fatty acids and carotenoids) from proteins. This can be realized by cascaded extraction using high-pressure extraction methods. These methods have a relatively low environmental impact compared to conventional solvent extraction. Unit operations such as subcritical pressurized liquid extraction (PLE) using organic solvents (e.g. ethanol, ethyl acetate) or supercritical fluid extraction (SFE) using carbon dioxide can be applied sequentially to separate products according to their polarity. Both extraction methods operate at high pressure and moderate temperature and can thus preserve the nutritional value and techno-functionality of the recovered compounds (Liau et al. 2010; Mendes et al. 2003; Pieber et al. 2012). Furthermore, there are several suitable solvents that meet the requirements and regulations of the food and feed sectors. Other extraction techniques, which have already been described for the extraction of plant biomass, including ultrasound-assisted extraction (UAE), pulsed electric field extraction (PEF) and microwave-assisted extraction (MAE), are also at the focus of current research in order to adapt them for microalgae treatment (Parniakov et al. 2015; Pasquet et al. 2011; Plaza et al. 2012).

Review Questions

- What are the differences between heterotrophic, mixotrophic and photoautotrophic growth, and what are main advantages and disadvantages of each growth type?
- What makes microalgae so interesting concerning their composition of ingredients in comparison to terrestrial plants?
- Which criteria have to be met for a microalgae reactor system to achieve high biomass productivity as well as energy efficiency?
- What are the main challenges concerning cascaded utilization of microalgae biomass?

6.5 Economics of Primary Production

Christian Lippert

Tea plantation *Seeyok* in Darjeeling (India) July 2016 © Christian Lippert

Abstract When developing new bio-based products and assessing their market opportunities, the correct calculation of all expected unit costs is indispensable. The provision of natural resources from primary agricultural or forest production is an important cost component in this calculation. All renewable natural resources require a certain time to grow. For this reason, in order to correctly account for all external and internal net benefits of natural resources, it is important to calculate the related capital costs and model the biological growth over time. For permanent crops and woodland resources, it is particularly important to derive optimized single and infinite rotations for different kinds of plantations. For this purpose, the corresponding biological growth expectations need to be combined with an investment appraisal. This chapter introduces basic concepts dealing with interest calculation based on the existence of (economic) capital growth and biological growth.

Keywords Biological growth function; Investment appraisal; Capital budgeting; CostingDiscounting; Forest economics

Learning Objectives

After studying this chapter, you should be able to:

- Apply an investment appraisal with special regard to farm and forestry economics
- Model biological growth by means of the Euler method
- Combine simple biological growth models and investment appraisal to optimize single and infinite rotations for different kinds of plantations

- Identify optimal replacement times for long-lasting assets in agriculture and horticulture

In this chapter, Sect. 6.5.1 outlines basic concepts of compound interest calculation (i.e. capital growth) and illustrates reasons for and methods of discounting. Section 6.5.2 deals with simple ways to mathematically describe and simulate biological growth. Combining both approaches enables us to plan optimum resource use over time: in this context, we will identify optimum harvest (or rotation) times in forestry (Sect. 6.5.3) and determine the optimum replacement time for permanent crop plantations that continuously yield yearly benefits (Sect. 6.5.4). Our analysis will focus on private wood- and crop-related benefits. However, in Sect. 6.5.3 we will also briefly discuss how the inclusion of forest-related positive externalities (for a definition of externalities, see Sect. 10.4) from regulating or cultural ecosystem services affects harvest decisions and optimum forest use over time. As the important concepts are presented quite concisely here, the reader should refer to Perman et al. (2011) for more detailed explanations. An interesting application of the approach presented in Sects. 6.5.3 and 6.5.4 can be found in Guo et al. (2006).

6.5.1 Investment Appraisal (Capital Budgeting)

In real life, every resource use results in an intertemporal sequence of benefits (B_t) and costs (C_t). In this context, a net benefit of a given amount of money is usually considered less valuable the farther in the future it is expected to occur. Thus, future benefits (B_t) and costs (C_t) have to be compared with present ones (B_0 and C_0). The standard approach to making future net benefits equivalent to present net benefits is to *discount* the former by multiplying them with a so-called discount factor. Diminishing an expected future amount of money by means of discounting involves accounting for possible capital growth, because the present value of the future amount is the money that one would need right now (as initial principal sum) in order to obtain the given future value as the initial principal sum plus the accrued compound interest. Discounting can be performed either assuming a discrete process (illustrated in Sect. 6.5.1.1) or a continuous process (illustrated in Sect. 6.5.1.2) in time. Section 6.5.1.3 uses the example of electricity production to briefly illustrate the correct calculation of per unit costs (in this case costs per kilowatt-hour of electricity) when the relevant cost components are unevenly distributed over time.

6.5.1.1 Basic Concepts of Discrete Discounting

Assuming a discrete process with time steps of 1 year corresponds to the common approach taken in banking. Future net benefits or cash flows ($B_t - C_t$) are transformed into present values by multiplying $B_t - C_t$ by a *discount factor* $(1 + r)^{-t}$, where r is an interest rate that reflects the opportunity cost of capital. Opportunity costs are the benefits foregone from a hypothetical alternative use of the capital invested in the project under consideration. If the money had not been invested in this project, it could have been alternatively placed at an interest rate r. Future cash flows can only be compared to present cash flows ($B_0 - C_0$) by discounting. The discounted present value B_0 of a benefit B_t arising at the end of year t is given by

$$B_0 = \frac{B_t}{(1+r)^t} = B_t(1+r)^{-t}. \qquad (6.1)$$

Usually the so-called discount rate r to be chosen by the decision maker is the interest rate at which loans could be raised or the rate at which his own capital (equity) could be placed or a weighted average of these two interest rates (the weights corresponding to the shares of loans and equity used when investing). For example, assuming a discount rate of $r = 2\%$, the present value of an expected benefit of 100 € in $t = 5$ years is $B_0 = B_t(1 + r)^{-t} = 100\text{ €}\ (1 + 0.02)^{-5}$

= 100 € × 0.90573 = 90.57 €. In this case, 100 euros available in 5 years have the same value as 90.57 € today. In other words: one would have to place 90.57 € today at a rate of return r of 2% in order to obtain a benefit of 100 € in 5 years.

For simplicity, assuming in investment appraisal that all yearly benefits $B_1, B_2, \ldots, B_T$ and all yearly costs $C_1, C_2, \ldots, C_T$ related to a certain project are *payments in arrears*, which means that in each case, they occur exactly *after t years* ($t = 1, 2, \ldots, T$), whereas the benefit B_0 and the cost C_0 are to be obtained or to be paid right now, one obtains the *Net Present Value (NPV)* of the project:

$$\mathrm{NPV} = \sum_{t=0}^{T} (B_t - C_t)(1 + r)^{-t} \qquad (6.2)$$

As a general rule, a project is only worthwhile as long as its NPV is positive. If the NPV is negative, this means the project is unprofitable. Of course, the NPV strongly depends on the assumptions made regarding the discount rate r and when calculating the net benefits $B_t - C_t$. Therefore, careful sensitivity analyses should be performed when calculating NPVs. For instance, one should always analyse how the NPV is affected by a ceteris paribus change of the discount rate applied. The NPV declines sharply with increasing discount rate, especially for projects like forest plantations that yield main net benefits particularly late in the future.

The *discounted payback period* [year k in Eq. (6.3)] is the first period at which the summed up discounted net benefits of an investment are greater than or equal to zero, so that

$$\begin{aligned} \mathrm{NPV}_k &= \sum_{t=0}^{k} (B_t - C_t)(1 + r)^{-t} \\ &\geq 0 \quad \text{and} \quad \mathrm{NPV}_{k-1} \\ &= \sum_{t=0}^{k-1} (B_t - C_t)(1 + r)^{-t} < 0. \end{aligned} \qquad (6.3)$$

As long as future prices and costs contained in net benefits $\mathrm{NB}_t = B_t - C_t$ have been calculated at today's prices (i.e. not accounting for inflation), a real interest rate r (i.e. an interest rate adjusted for inflation) should be used when calculating the NPV. Where future net benefits already account for price increases due to inflation, the discount rate applied should be a nominal interest rate (i.e. the interest rate actually paid or received). For a given nominal interest rate rn and a given inflation rate in, the real interest rate r is

$$r = \frac{\mathrm{rn} - \mathrm{in}}{1 + \mathrm{in}} \qquad (6.4)$$

For instance, a nominal interest rate $\mathrm{rn} = 4\%$ and an inflation rate $\mathrm{in} = 2\%$ yields a real interest rate $r = (0.04 - 0.02)/(1 + 0.02) = 0.0196 = 1.96\ \%$. Hence, for a relatively low inflation rate in, one can say that the real interest rate r approximately corresponds to the nominal interest rate rn minus the inflation rate in.

If an NPV is greater than zero, in principle, the corresponding project is worthwhile. If there are two alternative projects with identical capital needs (or in the case of plantations, with identical land requirements), the project yielding the higher NPV is to be preferred. However, as the NPV depends on the amount of capital invested, in the case of projects that require different amounts of capital, one should also examine the internal rates of return for the different investment alternatives. The *internal rate of return IRR* is the *discount rate that*—for given net benefits ($B_t - C_t$)—*leads to an NPV of zero*:

$$\mathrm{NPV} = 0 = \sum_{t=0}^{T} (B_t - C_t)(1 + \mathrm{IRR})^{-t}. \qquad (6.5)$$

When calculating the IRR in this way, the implicit assumption is made that all positive net benefits (cash flows) obtained at the end of the different time periods $t < T$ can be reinvested at the corresponding IRR. For huge IRRs, however, this assumption is unrealistic. In such cases, a *modified IRR (MIRR)* is to be determined:

$$\mathrm{MIRR} = \sqrt[T]{\frac{\sum_{0}^{T} \mathrm{NB}_t^{\mathrm{pos}} (1 + \mathrm{rr})^{T-t}}{\sum_{0}^{T} \mathrm{NB}_t^{\mathrm{neg}} (1 + \mathrm{rf})^{-t}}} - 1. \qquad (6.6)$$

where $\mathrm{NB}_t^{\mathrm{pos}}$ are all cash flows $B_t - C_t$ that are positive and can be reinvested at a rate of return rr and $\mathrm{NB}_t^{\mathrm{neg}}$ are the absolute values of all cash flows $B_t - C_t$ yielding negative amounts of money that need to be financed at an interest rate *rf*.

Constant annual cash flows in arrears (i.e. a constant yearly rent or an annuity $\mathrm{NB}_t = B_t - C_t = \text{constant} = \mathrm{NB}$ for all $t = 1, \ldots, T$) can be transformed into one single present value applying the *Present Value Annuity Factor (PVAF)*:

$$\begin{aligned}\mathrm{NPV} &= \sum_1^T \mathrm{NB}(1+r)^{-t} \\ &= \mathrm{NB}\sum_1^T (1+r)^{-t} \\ &= \mathrm{NB}\frac{(1+r)^T - 1}{r(1+r)^T} = \mathrm{NB}\cdot\mathrm{PVAF}. \qquad (6.7)\end{aligned}$$

Thus, the PVAF transforms a *constant(!)* yearly payment *NB* (to be obtained for the next *T* years) into one single present value. Note that $t = 1, \ldots, T$ and that formula (6.7) applies for payments in arrears. In the case of a *perpetuity* (i.e. an 'eternal' annuity $\mathrm{NB}_t = \mathrm{NB}$ with $t = 1, \ldots, \infty$), the PVAF in formula (6.7) can be simplified:

$$\begin{aligned}\mathrm{NPV}_\infty &= \sum_1^\infty \mathrm{NB}(1+r)^{-t} \\ &= \mathrm{NB}\sum_1^\infty (1+r)^{-t} \\ &= \mathrm{NB}\frac{1}{r} = \mathrm{NB}\cdot\mathrm{PVAF}_\infty. \qquad (6.7\mathrm{a})\end{aligned}$$

NPV_∞ is the amount of money that one would have to place today at an interest rate r in order to obtain a rent $\mathrm{NB} = r\,\mathrm{NPV}_\infty$ every year again and again (and for the first time at the end of year 1) without ever depleting the calculated necessary capital stock NPV_∞.

The reciprocal value of the *PVAF* is the *capital recovery factor (CRF)*, which transforms a single present value or payment into *T* constant yearly payments *NB* in arrears (to be obtained after each year *t*; $t = 1, \ldots, T$):

$$\mathrm{CRF} = \frac{1}{\mathrm{PVAF}} = \frac{r(1+r)^T}{(1+r)^T - 1}. \qquad (6.8)$$

The capital recovery factor may also be used to convert the NPV of a project or investment into an average yearly profit (or loss) resulting from the corresponding project. For farmers, the notion of a yearly profit is easier to comprehend than the idea of an NPV that corresponds to the amount of money theoretically obtained when converting all project-related cash flows into present values and adding them up.

6.5.1.2 Basic Concepts of Continuous Discounting

Discrete discounting as introduced in the previous section is common business practice. However, continuous discounting by means of an interest rate ϱ that is applied continuously (at infinitely small time steps) to a capital stock K_t in order to add compound interest is easier to handle in mathematics than discrete discounting. Continuous capital growth K_t is described by means of Euler's number e (=2.71828…):

$$\begin{aligned}K_t = K_0\mathrm{e}^{\rho t} \Rightarrow \frac{\mathrm{d}K_t}{\mathrm{d}t} = \rho K_0 \mathrm{e}^{\rho t} \Rightarrow \frac{\mathrm{d}K_t}{\mathrm{d}t} \\ = \rho K_t \Rightarrow \frac{\frac{\mathrm{d}K_t}{K_t}}{\mathrm{d}t} = \frac{\dot{K}}{K_t} = \rho. \qquad (6.9)\end{aligned}$$

The unit of the capital growth rate ϱ is *% divided by the time unit* for which the capital growth function has been calibrated, e.g. *%/year*. Applying the formula for continuous compounding, one can again ask for the present value B_0 of a benefit B_t that will be available in t years:

$$B_t = B_0\mathrm{e}^{\rho t} \Rightarrow B_0 = B_t\mathrm{e}^{-\rho t}. \qquad (6.10)$$

Thus, the term $\mathrm{e}^{-\varrho\cdot t}$ is the *discount factor for continuous discounting*. Hence, given a discount rate of $\varrho = 2\%$, the present value of an expected benefit of 100 € in $t = 5$ years gives a present value $B_0 = 100\ € \ \mathrm{e}^{-0.02\times 5} = 90.48$ €. So, according to this calculation, in 5 years, 100 € have the same value as 90.48 € today. This is less than the 90.57 € found in the case of discrete discounting above using Eq. (6.1) at a discount rate of 2%. The reason for this discrepancy is that one needs slightly less money today in order to have 100 € in 5 years when compound interest (i.e. the interest on interest) is calculated and added continuously. Every discount rate r (for discrete discounting) can be transformed into an equivalent discount rate ϱ (for continuous discounting):

$$\begin{aligned} &B_0 = B_T(1+r)^{-T} = B_T \mathrm{e}^{-\rho T} \Rightarrow \\ &\rho = \ln(1+r). \end{aligned} \tag{6.11}$$

So, if $r = 2\%$, the equivalent rate $\varrho = \ln(1 + 0.02) = 0.01980 = 1.98\%$ and, for the example, $B_0 = 100\text{ €}\ \mathrm{e}^{-0.0198 \times 5} = 90.57$ €. In the case of continuous discounting, the real interest rate (ϱ) corresponds exactly to the difference between the nominal interest rate and the inflation rate (ϱn − in). If all cash flows $B_t - C_t$ always occur in arrears at the end of year t ($t = 1, \ldots, T$), we can write

$$\mathrm{NPV} = \sum_{t=0}^{T} (B_t - C_t)\mathrm{e}^{-\rho t}. \tag{6.12}$$

For constant net benefits in arrears $\mathrm{NB}_t = B_t - C_t = \mathrm{NB}(t = 1, \ldots, T)$, we obtain

$$\begin{aligned} \mathrm{NPV} &= \mathrm{NB}_0 + \sum_{t=1}^{T} \mathrm{NB}\mathrm{e}^{-\rho t} \\ &= \mathrm{NB}_0 + \mathrm{NB}\sum_{t=1}^{T} \mathrm{e}^{-\rho t} \\ &= \mathrm{NB}_0 + \mathrm{NB}\frac{\mathrm{e}^{\rho T} - 1}{(\mathrm{e}^{\rho} - 1)\mathrm{e}^{\rho T}} \\ &= \mathrm{NB}_0 + \mathrm{NB} \cdot \mathrm{PVAF} \end{aligned} \tag{6.13}$$

In the case of a *perpetuity* (i.e. an 'eternal' annuity $\mathrm{NB}_t = \mathrm{NB}$ with $t = 1, \ldots, \infty$), the *continuous discounting Present Value Annuity Factor (PVAF)* simplifies to $\mathrm{PVAF} = 1/(\mathrm{e}^{\varrho} - 1)$. Again, the capital recovery factor (*CRF*) transforming a single present payment into T yearly payments (always to be obtained at the end of year t; $t = 1, \ldots, T$) is given by the reciprocal value of the *PVAF*:

$$\mathrm{CRF} = \frac{1}{\mathrm{PVAF}} = \frac{(\mathrm{e}^{\rho} - 1)\mathrm{e}^{\rho T}}{\mathrm{e}^{\rho T} - 1}. \tag{6.14}$$

In the special case of a *constant flow of money throughout the whole year* NB_{fl} (i.e. a constant yearly amount $\mathrm{NB}_{\mathrm{fl}}$ is equally distributed over the year t, $t = 1, \ldots, T$), the money obtained at every time span Δt amounts to $\mathrm{NB}_{\mathrm{fl}} \cdot \Delta t$. Assuming infinitely small time steps $\Delta t = \mathrm{d}t$, discounting and summing up these payments yields

$$\begin{aligned} \mathrm{NPV} &= \int_0^T \mathrm{NB}_{\mathrm{fl}}\mathrm{e}^{-\rho t}\mathrm{d}t = \mathrm{NB}_{\mathrm{fl}} \int_0^T \mathrm{e}^{-\rho t}\mathrm{d}t \\ &= \frac{1 - \mathrm{e}^{-\rho T}}{\rho}\mathrm{NB}_{\mathrm{fl}} = \mathrm{PVAF} \cdot \mathrm{NB}_{\mathrm{fl}}. \end{aligned} \tag{6.15}$$

where T approaches infinity—analogous to the case of discrete discounting [see Eq. (6.7a)]; the PVAF collapses to $1/\varrho$.

6.5.1.3 Calculating Average Cost-Covering Prices for (Bio-)energy

When comparing different ways of producing energy, the average cost per unit (e.g. of electricity expressed in Euro per kWh) needs to be correctly calculated. In principle, this average cost corresponds to a hypothetical *cost-covering electricity price* ($P_t = P$) in Euro per kilowatt-hour (€/kWh) that is assumed to be constant over the years t. The International Energy Agency (IEA) calls this cost-covering electricity price *Levelized Costs of Electricity* (*LCOE*). To fully cover all costs, the present value of all benefits needs to be equivalent to the present value of all costs (general representation):

$$\sum_{t=0}^{T} P \cdot E_t(1+r)^{-t} + \sum_{t=0}^{T} H_t(1+r)^{-t}$$

$$= \sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t)(1+r)^{-t} \Rightarrow$$

$$\text{LCOE} = P = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E_0 + \sum_{t=1}^{T} E_t(1+r)^{-t}} \tag{6.16}$$

where I_t = Investment expenditures in year t; M_t = Operations and maintenance expenditures in year t; F_t = Fuel expenditures (if relevant) in year t; C_t = Carbon costs in year t (if relevant); D_t = Decommissioning costs in year t; H_t = Value of heat produced in year t (if relevant); r = real discount rate (here: discrete discounting, for continuous discounting, the discount factors $(1 + r)^{-t}$ are to be replaced by $e^{-\rho \cdot t}$); E_t = Electricity generation in kWh in year t; and $P = LCOE$ = Cost-Covering Electricity Price (Levelized Costs of Electricity) in €/kWh. Assuming that $E_0 = 0$ (i.e. no electricity can be produced during the initial year when the power plant is built) and that for $t = 1$ through T the yearly energy production $E_t = E$ is constant, we can write

$$P = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E \sum_{t=1}^{T} (1+r)^{-t}} = \frac{\sum_{t=0}^{T} (I_t + M_t + F_t + C_t + D_t - H_t)(1+r)^{-t}}{E \cdot \text{PVAF}}. \tag{6.16a}$$

Given that expenditures I_t occur at the beginning and costs D_t at the end of corresponding projects, it should be considered how an increasing discount rate r applied by decision makers affects the average cost calculation according to Eq. (6.16) with respect to the cost components I_t and D_t. An interesting application and comparison of LCOE for different renewable energy technologies is given in Kost et al. (2013).

6.5.1.4 Cost-Benefit Analysis and Environmental Externalities

Externalities related to natural and environmental resources use result mainly from regulating and cultural ecosystem services. Social losses from resource degradation associated with certain production activities need to be accounted for when carrying out thorough bioeconomic cost-benefit analyses or cost calculations. The monetary valuation of corresponding externalities is beyond the scope of this chapter. Here, in the context of investment appraisal, we concentrate on how to find an adequate discount rate to apply when dealing with environmental benefits (or possible benefits foregone) that occur partly far in the future. Many resource-use decisions have a long-term impact, especially when they lead to resource depletion or ecosystem degradation. Hence, when discounting future environmental benefits, two questions arise: (1) Should common economic net benefits be discounted in the same way as the value of ecosystem services linked to nature preservation? (2) Which discount rate should be chosen when dealing with very long time horizons exceeding our own lifetime?

1. To answer the first question, the ideas put forward by Krutilla and Fisher (1975) may be useful: Let $B(D)_t$ be the annual benefit (e.g. farm produce) valued at today's market prices arising in year t from the development of some pristine land (e.g. forestland or moor) that is converted to farmland in year $t = 0$. $C(D)_t$ is the corresponding annual cost incurred when purchasing all inputs necessary to maintain production. These costs are also valued at present market prices. In contrast, $B(P)_t$ is the social benefit resulting from the ecosystem services provided by the pristine land. These annual environmental benefits will be forgone once the land is converted. They may be referred to as benefits of 'wilderness' preservation. Also, these yearly benefits, which are

benefits foregone once the land is converted, are assessed based on today's price and income conditions. ϱ is a real discount rate for continuous discounting. (N.B.: inflation does not matter in this context, as it is simply a general price increase.) Then the NPV of the development project is

$$\mathrm{NPV} = \int_0^T \{B(D)_t - C(D)_t\}\mathrm{e}^{-\rho t}\mathrm{d}t - \int_0^T B(P)_t \mathrm{e}^{-\rho t}\mathrm{d}t, \tag{6.17}$$

the second integral being the overall environmental cost of the development project in terms of 'wilderness' benefits foregone. The interesting question now is how the values $B(D)_t$, $C(D)_t$ and $B(P)_t$ will evolve over time relative to each other. In this context, Krutilla and Fisher (1975) believe that the relative value of benefits from 'wilderness' preservation $B(P)_t$ is likely to increase over time when compared to the prices contained in $B(D)_t$ and $C(D)_t$. The reasons for this are (1) the prospects of ongoing economic growth and technical progress that will reduce the relative value of the net benefits $B(D)_t - C(D)_t$ resulting from the development of the pristine land, (2) supposed high-income elasticities of demand for certain ecosystem services from 'wilderness' in contrast to stagnating (or even decreasing) supply of such services and (3) lack of substitution possibilities for these ecosystem services. Assuming the value of benefits from 'wilderness' preservation is given by $B(P)_t = BP_0\ \mathrm{e}^{\alpha t}$ with BP_0 being its present value and α the rate at which this value grows over time, we can write

$$\mathrm{NPV} = \int_0^T \{B(D)_t - C(D)_t\}\mathrm{e}^{-\rho t}\mathrm{d}t - \int_0^T BP_0 e^{\alpha t}\mathrm{e}^{-\rho t}\mathrm{d}t \tag{6.18}$$

Further assuming that the annual benefit BP_0 is equally distributed over the year and that the 'wilderness' benefits could be enjoyed for an infinite number of years ($T \to \infty$) if pristine land was preserved, applying Eq. (6.15) yields

$$\begin{aligned}\mathrm{NPV} &= \int_0^T \{B(D)_t - C(D)_t\}\mathrm{e}^{-\rho t}\mathrm{d}t - BP_0 \int_0^\infty \mathrm{e}^{-(\rho-\alpha)t}\mathrm{d}t \\ &= \int_0^T \{B(D)_t - C(D)_t\}\mathrm{e}^{-\rho t}\mathrm{d}t - \frac{BP_0}{\rho - \alpha}.\end{aligned} \tag{6.19}$$

Hence, the larger the assumed growth rate α (i.e. the future relative value increase of ecosystem services emanating from pristine land), the less likely it is that the project should go ahead. When the rate α is close to or even equals the discount rate ϱ, the development project should not be implemented (as then $BP_0/(\varrho - \alpha) \to \infty$). One should be aware that in practice, no matter what the assumed values of $B(D)_t$, $C(D)_t$ and $B(P)_t$ are, the project decision finally made by policy-makers strongly depends on their individual discount rates as well as on their assumptions of how the scarcity of 'wilderness'-related ecosystem services will increase in the future.

2. Applying a high discount rate in cost-benefit analysis when future environmental benefits are at stake means that these benefits receive a particularly low weight (the lower the farther in the future they occur). When increasing the discount rate applied, the NPV of a development project that contains environmental costs as future benefits forgone is then more prone to become positive. This is the case at least as long as the initial investment cost is relatively small and especially when the useful life of the project is much shorter than the expected time span during which the corresponding environmental impacts are relevant. One may think about nuclear energy and its very long-lasting environmental impact in this context.

Discounting future generations' benefits foregone entailed by today's resource use means systematically diminishing the opportunity costs inflicted on people living in the future. It is an ethical issue whether this is acceptable or not. It is frequently argued that the *social discount rate*, applied by a benevolent government explicitly accounting for the welfare of future generations, should be lower than common *private discount rates*, applied by private decision makers who are planning for their own business and usually deal with time horizons covered by their expected lifetimes. However, there may also be reasons for using relatively high social discount rates in project appraisal: firstly, this is not always unfavourable for the environment, as a high discount rate means not only attributing low weight to environmental damages in the far future but also lower weight to project benefits in the medium term (this aspect is more relevant the higher the initial investment cost). Secondly, applying relatively high discount rates is justified when believing that through economic growth, future generations will be wealthier than the current generation and able to substitute the lost environmental benefits in question. Thus, the answer to the question which discount rate to use then partly depends on how optimistic we are about future technical progress and resource substitution possibilities. When no substitute for an essential ecosystem service is in sight, a low discount rate is to be chosen, as suggested by *Krutilla* and *Fisher*. Following ideas expressed by Weitzman (1998), the discount rate applied may also depend on the time horizon *t* itself:

$$\mathrm{NPV} = \int_0^T \{B(D)_t - C(D)_t - B(P)_t\} \mathrm{e}^{-\rho_t t} \mathrm{d}t \text{ with } \rho_t = \rho(t) \text{ and } \frac{\mathrm{d}\rho}{\mathrm{d}t} \leq 0. \tag{6.20}$$

This involves using higher discount rates (derived from common market interest rates) for the relatively near future or for time periods within the decision makers' own expected lifetime. For the remote future, lower discount rates should be applied. This last point is all the more relevant as one does not believe in ongoing future growth of wealth.

6.5.2 Biological Growth Functions

When trying to optimize the use of a renewable resource, one needs to describe the development of the corresponding resource stock over time. Often it is adequate to describe biological growth as a function of current stock volume S_t. Defining

$$\frac{\mathrm{d}S_t}{\mathrm{d}t} = S'(t) = \dot{S} = \text{rate of change}, g(S_t) = \frac{\frac{\mathrm{d}S_t}{\mathrm{d}t}}{S_t} = \frac{\dot{S}}{S_t} = \text{growth rate of the stock},$$

then $G(S_t) = g(S_t) \cdot S_t$ is the biological growth function or regeneration function giving the related net biological growth $G(S_t)$ for every stock size S_t. In the simplest case when the rate of change ($\mathrm{d}S_t/\mathrm{d}t$) is proportionate to the current stock (meaning that $g(S_t) = g$ is a constant), we have exponential growth (see the dotted graph and the corresponding differential equation in Fig. 6.35).

However, an undisturbed evolution of the wood volume of a plantation is more likely to correspond to the simple logistic growth displayed in Fig. 6.35. For small stock sizes S_t, the value of the bracket in the differential equation for logistic growth is close to 1. Thus, at the beginning, there will be exponential growth; then, the growth rate of the stock will continuously decline until the stock volume asymptotically approaches an upper limit. The quadratic growth function or regeneration function $G(S_t)$ leading to logistic growth is said to be density dependent (the growth depending on plant or population density). $G(S_t)$ is a differential equation as the derivative of S_t is a function of S_t itself:

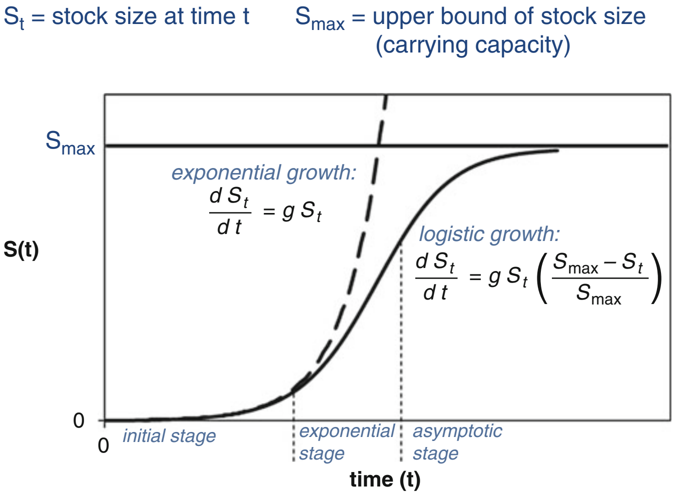


Fig. 6.35 Stock size over time for exponential growth and for logistic growth

$$G(S_t) = \frac{\mathrm{d}S_t}{\mathrm{d}t} = gS_t\left(\frac{S_{\max} - S_t}{S_{\max}}\right) = gS_t - \frac{gS_t^{\,2}}{S_{\max}}. \tag{6.21}$$

Solving Eq. (6.21) for S_t yields the development of the stock volume over time for an initial stock size S_0:

$$S_t = \frac{S_{\max}}{1 - \left(\frac{S_0 - S_{\max}}{S_0}\right)\mathrm{e}^{-gt}}. \tag{6.22}$$

For convenience, when modelling the growth of a plantation for a certain codomain of time, function (6.22) may be approximated relying upon a cubic function $S_t = a{*}t + b{*}t^2 + c{*}t^3$ (a and b being positive parameters, c being a negative parameter).

However, there may be additional (e.g. harvest-related) factors influencing $\mathrm{d}S_t/\mathrm{d}t$ in every time period that further complicate the growth function and the resulting equation describing the stock volume over time S_t. In such cases and when there is a clear functional relationship between $\mathrm{d}S_t/\mathrm{d}t = S'(t)$ and S_t, we may rely on the *Euler method* (according to *Leonhard Euler*, 1707–1783) to model stock development over time. This method is a numerical procedure to approximately solve differential equations for which an initial value is known. Its basic principle is to calculate stock size $S(t_{k+1})$ at point in time $t_{k+1}(=t_k + \Delta t)$ by simply adding the change [derived from the known function $G(S_t)$] taking place during time period Δt to the stock size $S(t_k)$ at point in time t_k:

$$S(t_{k+1}) = S(t_k + \Delta t) \approx S(t_k) + S'(t_k)\Delta t. \tag{6.23}$$

If this procedure is repeated again and again, one obtains an approximation for the development of the stock volume $S(t_k)$ at consecutive points in time t_k with $k = 0, \ldots, T - 1$). The resulting time path $S(t)$ will be the more accurate the smaller the chosen time step Δt.

6.5.3 Forest Economics and Bioeconomic Modelling of Plantations

From an institutional economics point of view and accounting for different possible institutional settings, natural forests yield different kinds of resources. Forests provide renewable resources as *private goods*: resource units can be allocated on the margin (i.e. consumed in small units), and property rights are usually enforceable (e.g. timber in German forests). Other forest-related renewable resources are *common pool resources*: resource units can be allocated on the margin; there is rivalry in consumption, but excludability is only obtained at prohibitively high cost (e.g. mushrooms in German forests). Thus, whether a resource is a private good or a common pool resource depends on the specific distribution of property rights along with local institutions and transaction costs for the enforcement of property rights. In addition, forests yield several *environmental resources as public goods (or forest use-related positive externalities)* that cannot be allocated on the margin and whose beneficiaries usually cannot be excluded and do not affect each other's utility (i.e. non-excludability and non-rivalry in consumption) (e.g. many forest-related ecosystem services). Further examples of forest-related private or common pool resources are fuelwood, charcoal, pulpwood, timber, fruits, nuts, mushrooms, medicinal plants, honey, wild game, drinking and irrigation water. Examples of positive externalities are protection against landslides, recreational and aesthetic amenities, cultural ecosystem services and regulating ecosystem services including the provision of plant and animal habitats, soil formation and nutrient cycling, water and air quality regulation, waste decomposition, climate regulation and CO_2 storage. Hence, forests are multi-attribute assets, and this should be kept in mind when analysing optimum harvesting strategies. In the following sections, however, we will focus on wood production as in traditional forest management. Forest land or a forest plantation can be seen as a capital asset with intrinsic growth and often an opportunity cost as the land could be used otherwise. The objective is to maximize the NPV of a forest plantation. First, a single rotation will be considered (i.e. trees are planted and logged at age T, then the land is used for a non-forest purpose, e.g. for agriculture). Second, optimization will be performed for an infinite rotation (i.e. the same tree species are replanted after every clear-cutting). Third, we will briefly discuss how positive forest externalities affect optimum harvest strategies (for further information, see Perman et al. 2011).

6.5.3.1 Optimum Resource Use in a Single-Rotation Forest Model

Let kpl be the initial planting costs (at time $t = 0$); P today's price per unit of harvested timber; c the marginal harvest cost—so that $p = P - c$ is the so-called stumpage price (value of a timber unit free of harvest cost); R the opportunity cost of the forest land (e.g. agricultural land rent foregone); ϱ the real discount rate (continuous discounting); T the harvest age of the stock (i.e. the time when the plantation is to be clear-cut); and S_T the volume of the stock reached at time T. Thus, the harvest age T is to be chosen in a way that maximizes the following NPV:

$$\mathrm{NPV}(T) = -kpl - \int_{t=0}^{T} R\,\mathrm{e}^{-\rho t}\mathrm{d}t + pS_T\mathrm{e}^{-\rho T}. \tag{6.24}$$

As the land's opportunity cost is constant over time and applying Eq. (6.15), we get

$$\mathrm{NPV}(T) = -kpl - R\frac{1-\mathrm{e}^{-\rho T}}{\rho} + pS_T\mathrm{e}^{-\rho T}. \tag{6.25}$$

Calculating the first derivative of NPV(T) and rearranging the first-order condition $\mathrm{NPV}'(T) = 0$, necessary to achieve an optimum, we find

$$p\frac{\mathrm{d}S_T}{\mathrm{d}t} = \rho p S_T + R. \tag{6.26}$$

Consequently, the optimum harvest time T is reached when in the last year of forest use (in period T), the stumpage value of the last period's stock increase ($p\ S_T/\mathrm{d}t$ = additional income when waiting one more period) is equal to the interest to be earned when harvesting the whole stock ($\varrho\ p\ S_T$ = additional income when converting attained forest capital into cash) plus the opportunity cost of the land (R = additional income when using the land alternatively, e.g. for crop production). If the value increment from forest growth on the left-hand side of Eq. (6.26) is still greater than the opportunity cost of bound capital and land displayed on the right-hand side, it is still better to wait with the harvest and let the forest grow instead of capitalizing on the harvested wood. One could also say that we are comparing possible biological growth with economic growth possibilities (a truly 'bioeconomic' consideration). Rearranging the optimum condition slightly (6.27) yields

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R}{pS_T}. \tag{6.27}$$

implying that, at optimum harvest time T, the growth rate of the stock should be equal to the real interest rate plus the relative capital increase from alternative land use, or the growth rate of the stock should equal the possible rate of return of the capital bound (incl. land). The latter is the possible capital growth rate when converting the forest (the natural capital) into cash.

6.5.3.2 Optimum Resource Use in an Infinite-Rotation Forest Model

Where there are no alternative land-use possibilities (i.e. $R = 0$), it does not really make sense to assume that the forest land will be left fallow after T years. If the forest plantation turned out to be profitable ($\mathrm{NPV}(T) > 0$), the plantation should be replaced after clear-cutting in year T, which means that at time T, the NPV (T) can be obtained again. But then, as long as all assumed price and cost parameters do not change, reforestation should be done again and again at points in time T, $2T$, $3T$, …, nT with n approaching infinity. This is the case for an *infinite* (sequence of) *rotation*(s) with T being the *rotation length*. As the NPV of an infinite rotation is the NPV of the first rotation plus the discounted (residual) value of the land after clear-cutting in year T, we can write

$$\mathrm{NPV} = -kpl + pS_T\mathrm{e}^{-\rho T} + \mathrm{NPV}\,\mathrm{e}^{-\rho T}. \tag{6.28}$$

Hence, the NPV of an infinite rotation is the NPV due to the land use of the first T periods plus the discounted NPV of the same infinite rotation. This second term accounts for the still infinite sequence of rotations from period T onwards. Solving Eq. (6.28) for NPV gives

$$\mathrm{NPV}(T) = \frac{pS_T\mathrm{e}^{-\rho T} - kpl}{1 - \mathrm{e}^{-\rho T}}. \tag{6.29}$$

A similar expression could be deduced for the case of discrete discounting. Again, we can use the first-order condition $\mathrm{NPV}'(T) = 0$ to derive an optimum condition that needs to be fulfilled at harvest time T (and at times $2T$, $3T$, …, nT as well). This way, we obtain the so-called Faustmann rule (in honour of *Martin Faustmann*, 1822–1876):

$$\frac{p\frac{\mathrm{d}S_T}{\mathrm{d}t}}{pS_T - kpl} = \frac{\rho}{1 - \mathrm{e}^{-\rho T}}. \tag{6.30}$$

Solving Eq. (6.29) for kpl and entering the corresponding term for kpl into (6.30) yields, after rearranging a condition that is quite similar to condition (6.27) above:

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{\rho\mathrm{NPV}}{pS_T}. \tag{6.31}$$

The rotation length T is to be chosen so that when harvesting, the growth rate of the stock just equals the interest rate plus the relative capital increase due to the average land rent from future forest use. Again, the possible growth rate of the stock should be equal to the possible rate of return of the capital bound (incl. land). ϱNPV is the perpetuity (the 'eternal' annuity) from continuous forest use. In this context, the NPV is also referred to as 'site value' of the forest land (i.e. the maximized NPV from an infinite number of rotations).

6.5.3.3 Forest Model with Positive Externalities

Finally, it should be discussed how the forest externalities mentioned above affect wood-harvesting strategies. For simplicity, let us assume that these external benefits FE

(e.g. from habitat support or landscape amenities) occur after a certain time once the forest has been planted and remain constant until clear-cutting at time T. From a social point of view, and according to the same reasoning that led to condition (6.27) for the single-rotation forest model, the optimum condition to determine harvest time now is

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R - \mathrm{FE}}{pS_T}. \qquad (6.32)$$

The opportunity cost of the land (R) is diminished by the welfare gains due to forest externalities (FE). As the right-hand side of this optimum condition is smaller now than in the case of $\mathrm{FE} = 0$, and considering the growth rate of the stock is declining because of logistic growth, the optimum harvest age T will occur later than when merely considering wood benefits. Not surprisingly, positive forest externalities will delay clear-cutting and forest replacement by an alternative land use.

The optimum conditions for traditional forest management derived in this chapter should be applied when dealing with certain types of plantations. However, one should be aware that, given the multiple beneficial ecosystem services related to the existence of natural forests, clear-cutting of forests should be avoided. According to § 5 (3) of the *German Federal Nature Conservation Act*, forests should be managed sustainably without clear-cutting. *Selective forestry* to obtain near-natural forests is to be implemented instead. This allows for continuous wood harvest and natural regeneration. The issue of optimum forest use over time then turns out to be a question of realizing *maximum sustainable yield*. In principle, this means the forest manager needs to find the stock volume at which the forest regeneration function $G(S)$ [see Eq. (6.21) as an example] is at its maximum.

6.5.4 Determining the Optimal Replacement Time in Agriculture and Horticulture

The reasoning applied in Sect. 6.5.3 can be easily extended to assets or projects that also involve benefits and costs between time periods 0 and T (e.g. hop gardens, rubber plantations, greenhouses). In addition to the symbols already introduced, let ka be the initial investment cost for the asset considered (at time $t = 0$) and Ra_T the residual value (salvage value) of the asset that is received at time T. The NPV of such an investment is

$$\begin{aligned}\mathrm{NPV}(T) &= -ka \\ &\quad + \sum_{t=1}^{T} (B_t - C_t - R)\mathrm{e}^{-\rho t} \\ &\quad + Ra_T \mathrm{e}^{-\rho T}. \end{aligned} \qquad (6.33)$$

The ex ante *optimum useful lifetime T* is again obtained by considering $\mathrm{NPV}'(T) = 0$ leading to

$$B_T = C_T + R - \frac{\mathrm{d}Ra_T}{\mathrm{d}t} + \rho Ra_T. \qquad (6.34)$$

This means the optimum lifetime of the investment is reached once the marginal benefit when using the asset one more period (B_T) is equal to the marginal cost of using it one more period. This marginal cost consists of additional operating costs (C_T) plus the opportunity cost of the land needed (R) plus the amount of the loss due to a reduced residual value ($\mathrm{d}Ra_T/\mathrm{d}t$ is negative and corresponds to depreciation of the asset) plus the interest forgone because the residual value is cashed one time period later (ϱRa_T).

In the case of identical replacement of the asset, analogous to Eq. (6.29), the NPV of an infinite sequence of the corresponding investment is

$$\mathrm{NPV}(T) = \frac{-ka + \sum_{t=1}^{T} (B_t - C_t)\mathrm{e}^{-\rho t} + Ra_T \mathrm{e}^{-\rho T}}{(1 - \mathrm{e}^{-\rho T})} = \frac{\mathrm{NPV}(T)^*}{(1 - \mathrm{e}^{-\rho T})}. \tag{6.35}$$

NPV(T)* being the NPV of a single investment. For discrete discounting, the NPV of an infinite identical replacement is

$$\mathrm{NPV}(T) = \frac{-ka + \sum_{t=1}^{T} (B_t - C_t)(1+r)^{-t} + Ra_T (1+r)^{-T}}{1 - (1+r)^{-T}} = \frac{\mathrm{NPV}(T)^*}{1 - (1+r)^{-T}}. \tag{6.36}$$

Calculating NPV(T) using Eqs. (6.35) or (6.36) for different possible replacement times T and thus searching for the highest NPV lead to the optimum ex ante *replacement time* of the asset. Ex ante *decision situation* here means that the corresponding asset is not yet purchased or the plantation not yet implemented, and one wants to determine the optimum useful life given expected prices and costs before starting the project.

In contrast, in an ex post *decision situation*, the asset or the plantation is already being used, and one wants to know when to replace it by an alternative or identical land use. Very important when making ex post decisions on how long to continue the use of an asset, a plantation or a forest stand, the initial investment costs of the *present* use (*kpl* or *ka*) do not matter! Once an investment has been implemented, these initial costs are so-called sunk costs already paid for in the past. Such sunk costs cannot be recovered. In ex post decision situations, marginal net benefits of the current land use have to be compared to average net benefits (ANB) of the considered possible future land use:

$$B_T - C_T + \frac{\mathrm{d}Ra_T}{\mathrm{d}t} - \rho Ra_T = \mathrm{ANB}. \tag{6.37}$$

As long as the marginal net benefit when continuing to use the old asset [i.e. the left-hand side of Eq. (6.37)] is still greater than the ANB of the future use, the current use should be continued. ANB is to be calculated for the new replacing investment using Eqs. (6.33) or (6.35). Note that in Eq. (6.37), $\mathrm{d}Ra_T/\mathrm{d}t$ (i.e. the depreciation in period T) is usually negative.

Review Questions

- Explain the basic difference between discrete and continuous discounting.
- In which cases can one make use of a *Present Value Annuity Factor* (*PVAF*) when calculating a *Net Present Value* (*NPV*), and under which conditions does this factor collapse to 'one divided by the discount rate'?
- Explain and illustrate by means of a formula containing the main cost components how to calculate cost-covering electricity prices for a biogas plant.
- Following the ideas of *Krutilla* and *Fisher*, what are the reasons the future value of certain ecosystem services (i.e. benefits related to 'wilderness' preservation) should be discounted at relatively low discount rates in a cost-benefit analysis?
- Explain the basic concept of the *Euler method*.
- Write down and explain the *Net Present Value* (*NPV*) of (a) *a single-rotation forest model* and (b) *an infinite-rotation forest model*—with reference to the growth rate of the stock. For both cases, give an optimum condition that is to be met when maximizing the NPV.
- Explain how to identify the ex ante *optimum useful lifetime* of an agricultural asset (e.g. a rubber plantation) (a) in the case of an alternative land-use opportunity and (b) in the case of identical replacement.
- Give a rule for the optimum replacement time in an ex post *decision situation*, and explain why so-called sunk costs do not matter in this context.

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