6.1 Agricultural Production

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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

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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.

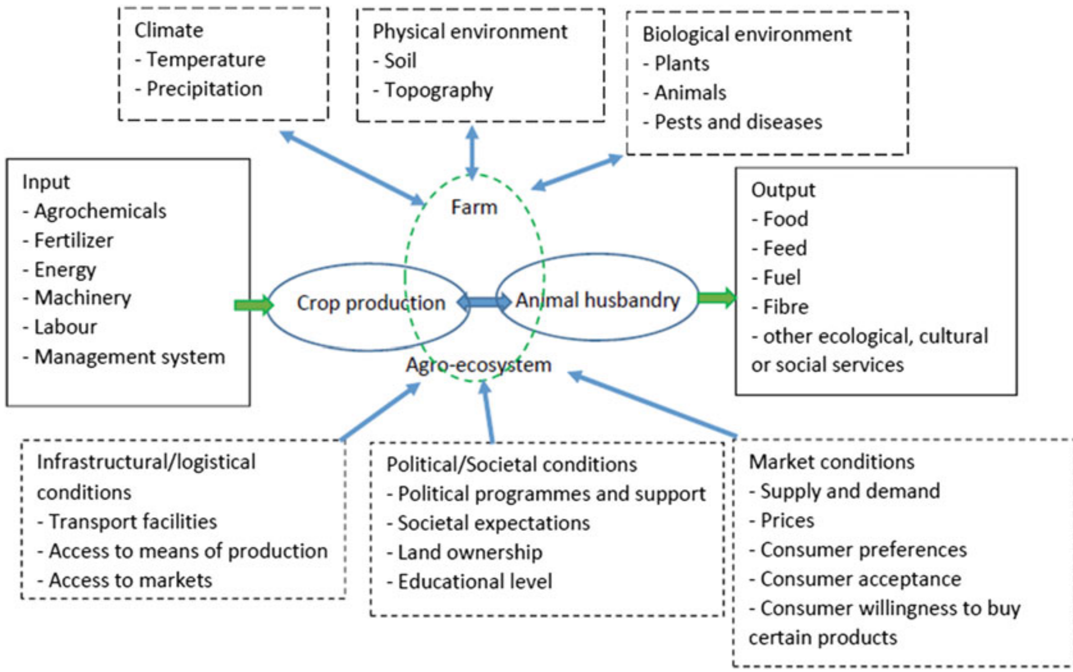

Fig. 6.4 Agricultural production systems and their determinants

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.

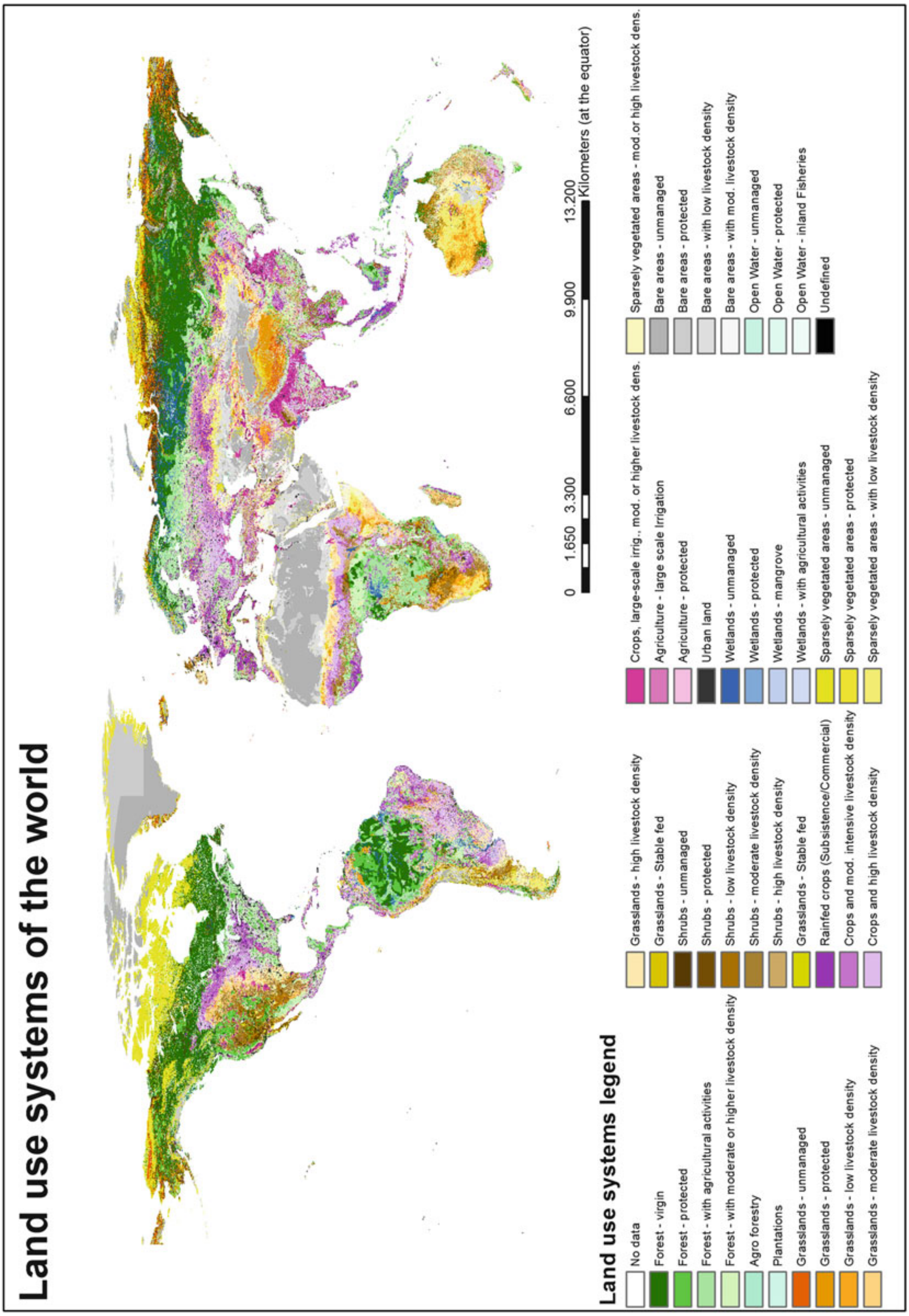

Fig. 6.5 Land use systems of the world (based on Nachtergaele and Petri 2008)

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

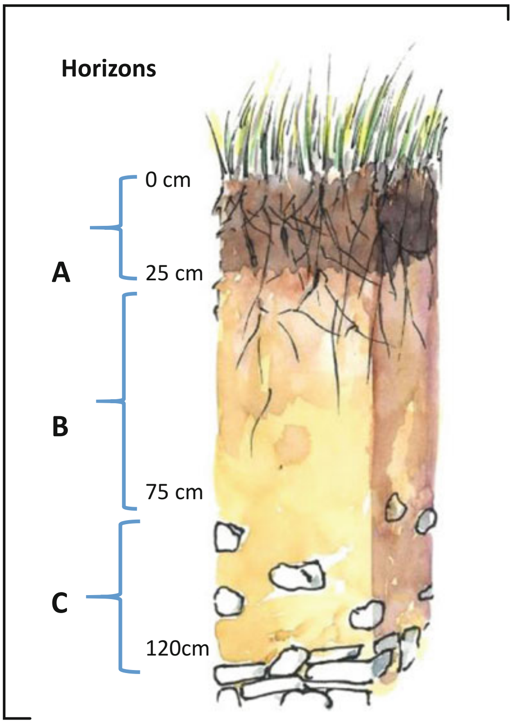

Fig. 6.6 Typical soil profile with different horizons © Ulrich Schmidt

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 run-off (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.

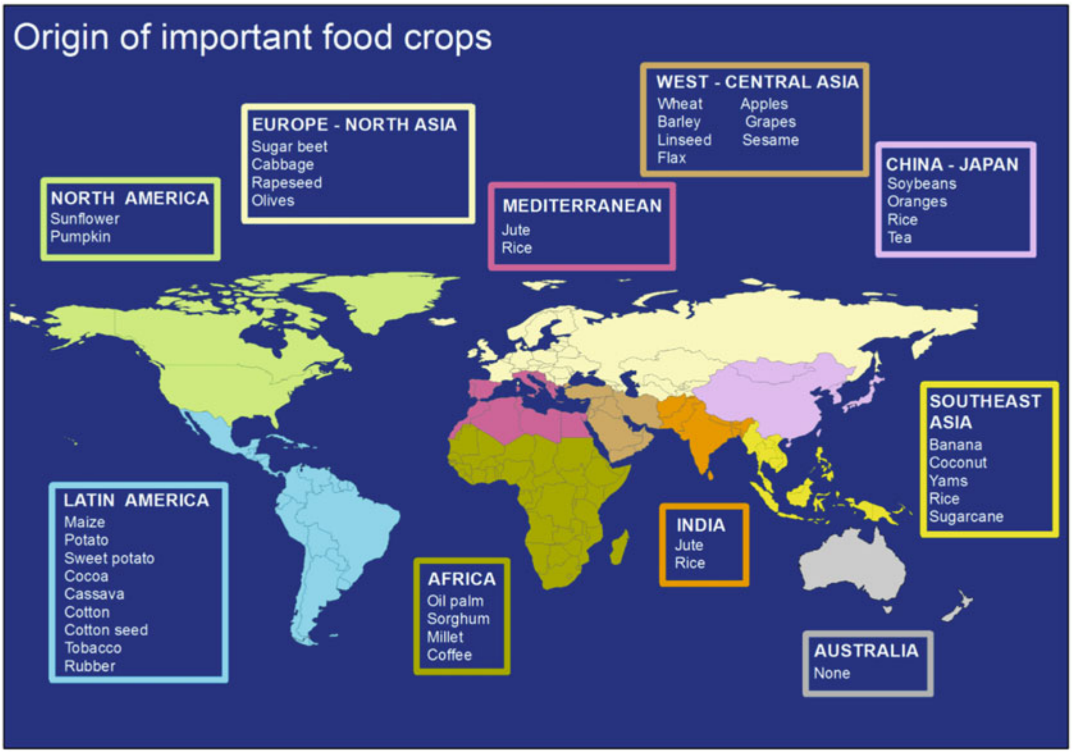

Fig. 6.7 Origin of important food crops (based on Khoury et al. 2016)

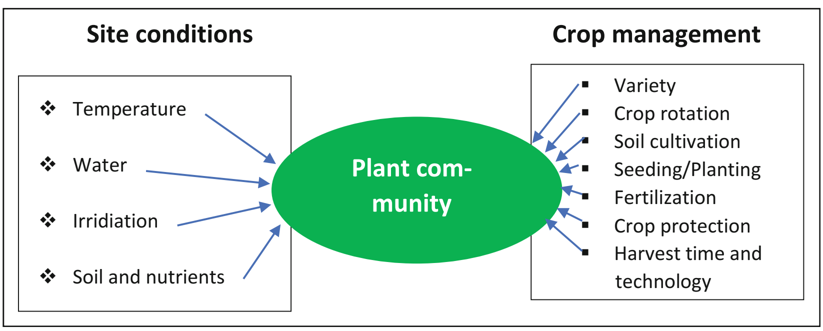

Fig. 6.8 Factors determining success of crop production

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).

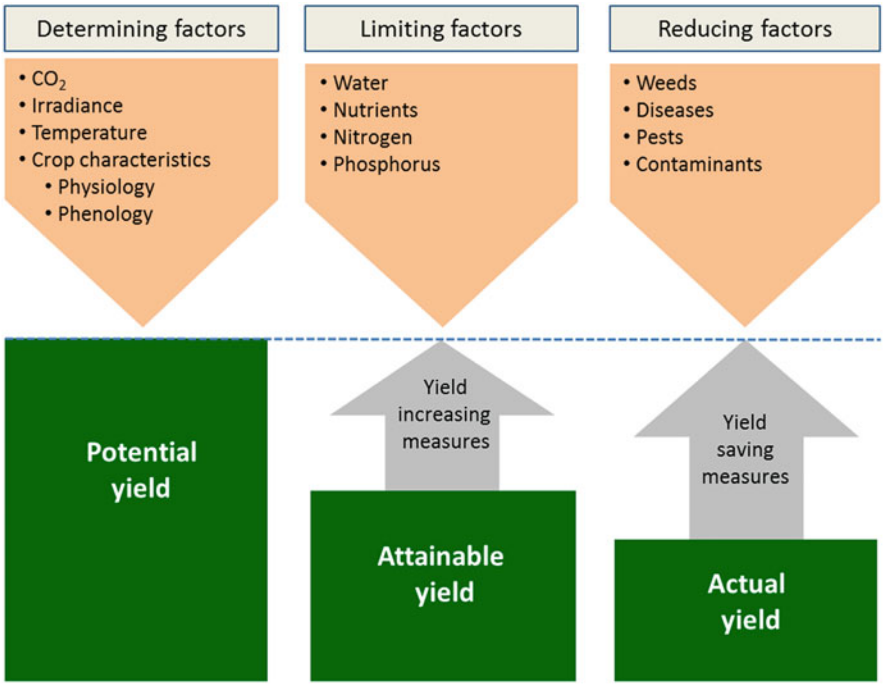

Fig. 6.9 Determination of crop yields (adapted from Rabbinge 1993)

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).

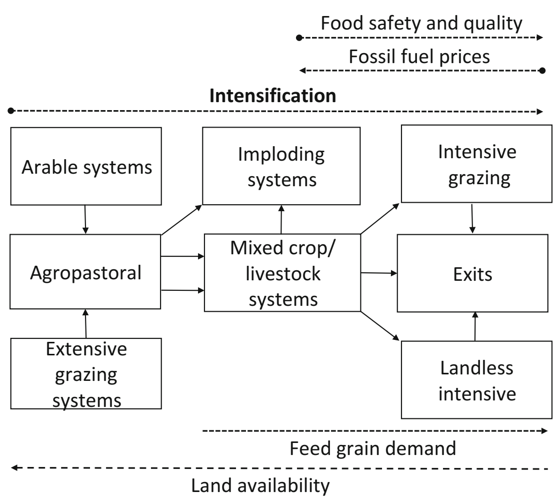

Fig. 6.10 Schematic presentation of development pathways of main livestock production systems and selected main drivers (from World Bank 2009)

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

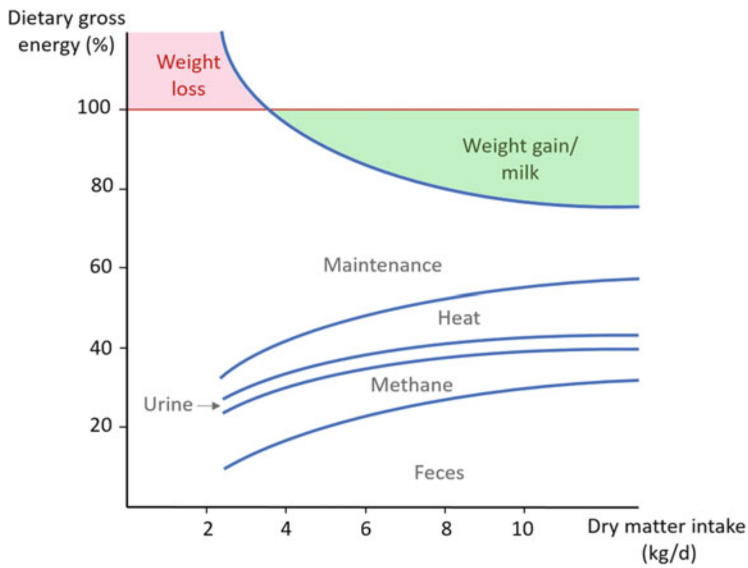

Fig. 6.11 Changes in the proportion of energy lost in faeces, urine, heat production and methane and in the proportion of energy used for maintenance and weight gain/milk production with increasing feed intake in ruminants (From van Soest 1994; based on Mitchell et al. 1932)

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.

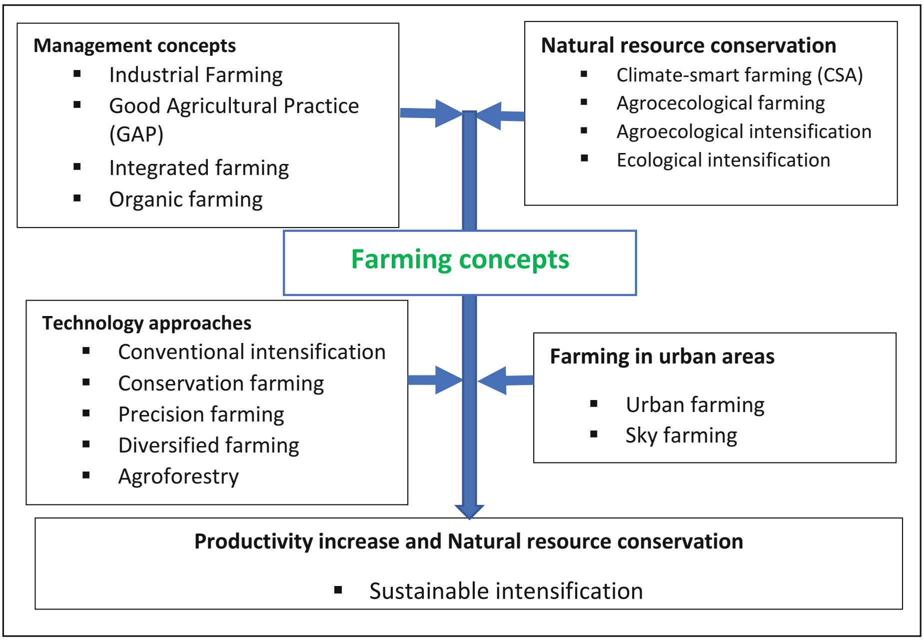

Fig. 6.12 Farming concepts

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.

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 $CO_{2equivalents}$ 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 $CO_{2equivalents}$/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

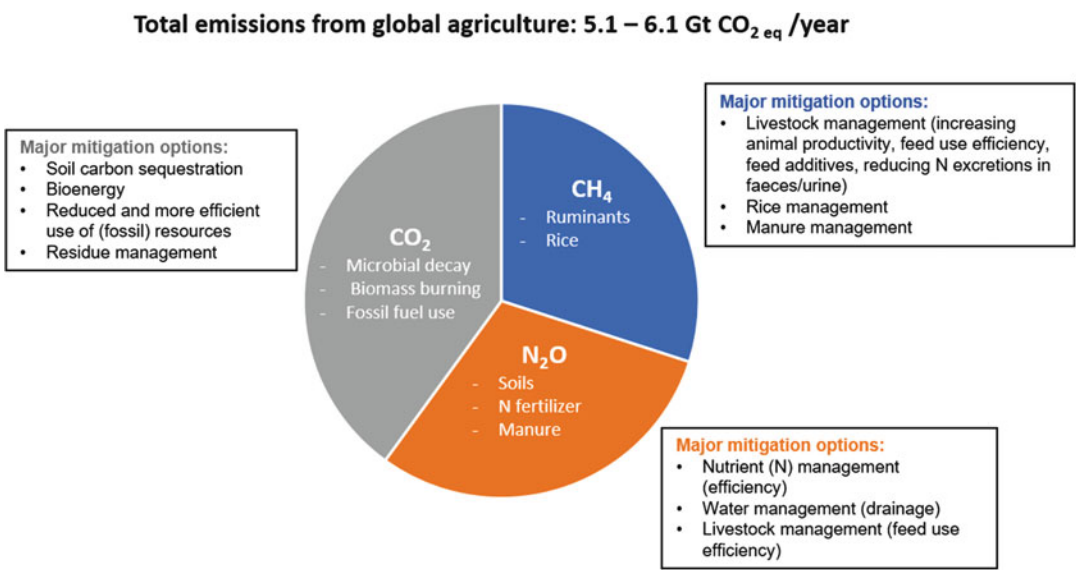

Fig. 6.14 Greenhouse gas emissions from global agriculture in Gt $CO_{2equivalents}$/year together with major emission sources. Boxes indicate major GHG mitigation options in agricultural management (data from Smith et al. 2007)

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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van den Born GJ, van Minnen, JG, Olivier JGJ, Ros JPM (2014) Integrated analysis of global biomass flows in search of the sustainable potential for bioenergy production, PBLY report 1509, PBL Netherlands Environmental Assessment Agency