1 Introduction

1.1 Research motivation, questions and scope

Agricultural and forestry resources have been processed for industrial uses for centuries. They have gained renewed attention every time access to fossil feedstocks was disturbed. The recent drive towards the use of **renewable raw materials** for commodity production appears to be sustained. The main drivers of this development are resource **cost and supply security**, **environmental issues** and economic **development of rural areas**. Emphasis on the three drivers differs from country to country. For private businesses, the use of renewable raw materials must be profitable. Otherwise investments and commercial operations will not be sustainable. Researching the **economics** of renewable raw materials is therefore an essential task during the ongoing resource shift in commodities production.

Numerous new applications of a diverse range of biomass types beyond traditional food and wood product processing have been discussed, developed or implemented (e.g. Lange 2007, Fritsche et al. 2012). The application of biomass for industrial production links agricultural or silvicultural feedstock provision with process industry operations. This forms integrated **agro-industrial supply chains** designed for producing **bio-commodities**.

Among the potentially large variety of bio-commodities, **fuels** play an important role. Because of substantial government support, this was the first new biomass application to gain global commercial significance (Walter et al. 2008). Yet the potential for fuels obtained from vegetable oil, sugar and starch is limited by restricted land and farming inputs. Possible competition with food production has caused debates and controversies (FAO 2008). Hence, there is a strong interest to further exploit this potential by developing pathways based on residual, by-product or unused resources from agriculture and forestry. It would be the next step towards an economy less reliant on fossil resources supplied by a small number of global producers (Mueller et al. 2011).

The major share of agricultural and forestry by-products is composed of **lignocellulose**, the structural component of all plants including wood (Kim and

Dale 2004). Lignocellulose-based or ‘cellulosic’ bio-commodity businesses however face major **obstacles for profitable realisation** because of high production costs and technological uncertainties.

For economic profitability in an established commodity market like the transportation fuel sector, the ability to achieve low **production costs** is particularly important. Despite technological feasibility of different production concepts, commodity products from lignocellulose must gain further ground to compete with more mature pathways based on sugar or starch (e.g. Hettinga et al. 2009, EPA 2013). The technologies are still associated with high conversion costs (Viikari et al. 2012, Trippe 2013). But despite the high costs of pre-mature technologies, **feedstock and logistics costs** remain the largest or at least one large component of production costs for cellulosic bio-commodities (Chandel et al. 2010, Haase 2012). Dispersed feedstock bases seem to constrain the establishment of large-scale facilities which are required to permit low enough conversion costs.

The restrictions imposed by the **trade-off** between increasing feedstock **transport costs** and decreasing costs driven by **economies of scale** can be eased by innovative design of the entire supply chain from primary feedstock sourcing to final product distribution. Implementation of **decentralised pre-processing** technologies, optimised plant capacity set up, transport system selection as well as efficient use of capital-saving and more readily accessible **existing infrastructure** rather than green-field developments are promising measures. These can contribute to drive down costs of cellulosic bio-commodities (Batsy et al. 2012, Kim and Day 2011). There is thus a rationale to investigate these measures for different technologies, feedstocks and regions. Two fundamental research questions result for this work:

1) To assess the potential of supply chain design: What is the most favourable supply chain configuration taking pre-processing and transport options, existing infrastructure and profitability requirements into account?

2) Regarding the trade-off between economies of scale and feedstock transport costs: Does innovative supply chain design enable operation of larger, more economical plants, and which quantities can be produced at which costs for specific case studies?

Pre-processing technology options like pelletisation, torrefaction and pyrolysis have been the subject of studies focussing on thermochemical fuel and bulk chemical production from agricultural raw materials, an important technology platform for lignocellulose utilisation (e.g. Czernik and Bridgwater 2004, Uslu et al. 2008). Saccharification of lignocelluloses and subsequent **fermentation** of sugars into organics like **ethanol** which can be used as fuels but also as bulk and intermediate chemicals is another important technology platform of lignocellulosic biomass usage. It also faces the challenges of the trade-off between transport costs and economies of scale (Hoekman 2009).

Recent studies have however shown that a wider range of pre-processing technologies than previously assumed might be available for the fermentation platform (Chiaramonti et al. 2011, Kumar et al. 2012a, Lian et al. 2010). Likewise, only few studies have looked into potential benefits from selecting rail and ship transport as logistics options in cellulosic ethanol supply chains. This merits studying the economics of ethanol from lignocellulose through saccharification and fermentation with these new options taken into account, and a comparison with results obtained for the thermochemical platform.

Uncertainties in agricultural feedstock supply add to conversion process uncertainties (Awudu and Zhang 2012). Several important factors influencing the economics of bio-commodities are subject to commercial, technological and natural **uncertainties and variability**. This raises three more research questions for this work:

3) How can the impacts of uncertainty and variability related to agricultural raw materials and immature technologies be quantified?

4) How relevant are uncertainty and variability for economic performance?

5) How can uncertainty and variability be factored in for decision making on commercial realisation of bio-commodity production operations?

Analysing uncertainties and variability provides more information for decision makers, permitting **quantification of impacts on economic performance**. Single values for key economic indicators obtained from deterministic analyses are supplemented by probability distributions for key indicators and by assessments of the robustness of supply chain designs obtained from stochastic analyses. It is also a starting point to design the supply chain in a way that

minimises negative impacts at an early stage in the commercialisation process.

Addressing the open research questions requires an economic evaluation that includes strategic supply chain design and an uncertainty and variability analysis. As there is hitherto no research framework available for this task (see chapter 3), a **comprehensive framework** must be developed which draws on existing methodologies and which extends them with new approaches where necessary.

The research framework suggested in this work primarily takes the perspective of private sector, agribusiness and process industry **decision makers** in single businesses, corporations, groups of companies and whole industry organisations. Nevertheless, further stakeholders with a related interest can equally profit from the presented approaches and results for their decisions. This includes other supply chain participants like prospective feedstock providing farmers and end product users, commercial or academic developers of technologies as well as institutions and agents in the public sector.

Amid the ongoing internationalisation of the global economy and its players, commercial realisation of fuels and chemicals from agricultural and forestry by-products will likely take place across international supply chains integrating different industries and operations (Uslu et al. 2008, Walter et al. 2008). To provide valuable decision support, a research framework for economic evaluation must be capable of capturing details at a level sufficient to examine options for **different technologies, feedstocks and regions**. It must also be **flexible and adaptable** to investigate the variety of relevant options. Finally, the framework has to be applicable with the effort and within the time acceptable for capital investment or entering decisions.

Against this background, the **primary objective** of this work is to develop a practical, flexible and adaptable research framework for economic evaluation of bio-commodity production with integrated strategic supply chain design and uncertainty analysis. This framework shall be applied to investigate cellulosic fuel production and to examine the potential of innovative supply chain design and the impacts of uncertainties and variability on economic performance.

The **secondary objective** is to contribute to the understanding of emerging bio-commodity-based industries. Profitably and efficiently producing food, feed, energy products, chemicals and materials requires approaches that cross traditional boundaries of research fields and industry sectors. Integrative research frameworks can form the basis for successfully engineering and managing such operations.

1.2 Approach and outline

The research questions for this work raised in section 1.1 target three aspects (Figure 1.1).

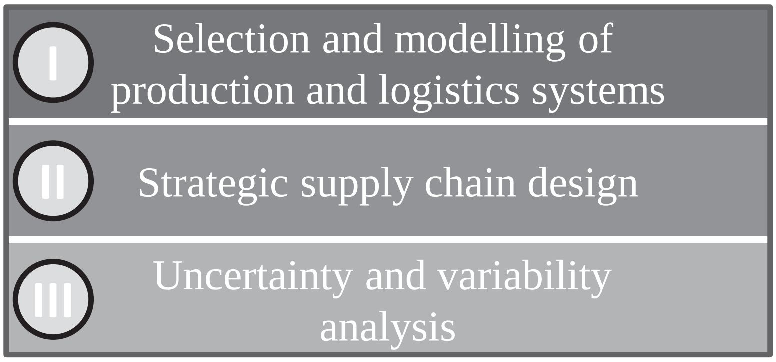

Figure 1.1 Research aspects

The first aspect is **selection and modelling** of operations. These include feedstock and fuel production systems as well as logistics systems. Accounting for the environment of technological, natural, commercial and feedstock specific conditions requires techno-economic modelling. Linkable modules with key indicators subject to technical and economic input parameters can represent production and logistics systems in the model.

The second aspect is analysing and comparing different **supply chain designs** to reveal economic performance and commercial potential of cellulosic ethanol production from selected feedstocks. The techno-economically modelled production and logistics systems can be combined to form supply chains. To obtain optimised but realistic configurations, supply chain design involves planning and optimisation tasks.

The third aspect is integrating **uncertainties and variability** into the research framework to show impacts and to identify starting points for how to mitigate negative effects.

Furthermore, **demonstration of extendibility and adaptability** of the developed modelling framework is necessary for the investigation of further technologies, feedstocks and regions.

The methodological framework addressing these aspects has to fulfil the requirements discussed in section 1.1. A comprehensive review of the related literature will point out how far existing methodologies can be applied and where extensions and new approaches have to be developed. A high degree of flexibility will ensure that investigators looking beyond the cases researched here can customise the elements. This way, different technologies and production concepts, feedstocks and industry sectors as well as regions and geographies represented by datasets and boundary conditions can be modelled. Supply chain design ideas and innovations can be tested within the same framework.

Special attention will be paid to usability for further research as well as practical decision support such as assessing whether investments into fixed capital should be made. Application of the framework will be carried out with reference to a selected case study of particular interest. To demonstrate the possibility of extension and further application to different technologies, feedstocks and regions, other case studies will subsequently be discussed as well. To answer the specific research questions, three levels of investigation are required (Figure 1.2):

Figure 1.2 Levels of investigation

1) A **research framework** that integrates techno-economic evaluation with supply chain design and uncertainty and variability analysis, and that is applicable to all bio-commodity production systems.
2) A **decision support system** that incorporates the research framework, is capable of delivering the requested results, and is easily adaptable to analyse different regions, feedstocks and technologies.

3) Application of the decision support system to a **case study** for specific feedstocks and technologies that allows for drawing of conclusions for cellulosic fuel and bio-commodity production in general.

To cover all research aspects and levels of investigation, the outline of this dissertation is the following.

Chapter 2 presents background information on bio-commodity production, particularly cellulosic fuel production. It introduces process industries in general and characterises the current drive towards a shift of the resource base in the energy and chemical industries. The chapter describes industrial applications of agricultural raw materials, lignocellulosic feedstocks and conversion technologies. The biochemical platform and its main product ethanol are discussed in detail.

In chapter 3, the literature on the economics of bio-commodity and cellulosic fuel production is reviewed to present the state of research. Conclusions from the literature review lead to the formation of a three step research framework for economic evaluation with integrated supply chain design and uncertainty analysis. In the following, this framework and its implementation in a decision support system are developed with reference to a case study. Chapter 3 introduces this case study of cellulosic ethanol production from sugar-cane by-products in Australia.

The subject of chapter 4 is the techno-economic modelling of prospective production and logistics systems that cover all operations of a cellulosic fuel supply chain. Methodologies introduced and applied for this step include technology selection and modelling, investment and cost estimation and economic project evaluation. The supply chain covers feedstock provision, logistics, pre-processing, fuel and chemicals production as well as distribution. Special attention is paid to the accurate modelling of pelletisation, torrefaction and pyrolysis as pre-processing options, and available means of transport for the biochemical, cellulosic ethanol supply chain.

Chapter 5 deals with supply chain design. For this step, approaches from location planning and strategic logistics planning are adapted and developed further. Decentralised ethanol production with a biochemical plant attached to each Australian sugar factory is analysed as the first concept. More options are available for the second concept of centralised ethanol production. In addition to other strategic planning tasks, an approach to solve the combinatorial problem for optimisation of feedstock sourcing is presented to generate a production configuration with the lowest minimum selling price for ethanol.

Chapter 6 establishes a simulation-based and model-integrated analysis of uncertainty and variability for technical and economic parameters. A two-level nested Monte Carlo simulation distinguishes uncertainty dissolving after the project becomes operational from ongoing variability over the project life-time.

Results for the whole supply chain of the cellulosic ethanol case study are presented in chapter 7. Probabilities and distributions of the minimum selling price of ethanol are shown and interpreted and the robustness of selected supply chain configurations is tested. Finally, implications for ethanol production from Australian sugar industry by-products and for cellulosic fuel production in general are discussed based on these results.

Chapter 8 centres on further applicability and research questions as well as on limitations of the developed framework. The gasification and Fischer-Tropsch synthesis platform is investigated as another lignocellulose conversion technology and compared with the results for ethanol. This is followed by a brief discussion of ethanol production from imported palm oil milling by-products from Papua New Guinea at a location in Japan. A critical review of the methods and results presented in this work follows to address limitations.

Chapter 9 completes the investigation with a results summary, final conclusions and an outlook.

2 Bio-commodities and cellulosic fuels

In this chapter, the economic and technological background of bio-commodity production and cellulosic fuel commercialisation is presented.

As fuels and chemicals are commodity products of the process industry, the characteristics of this sector are analysed to describe the environment into which bio-commodities are introduced. The production of bio-commodities creates new agro-industrial supply chains which integrates different characteristics of the agricultural and process industries.

A brief but comprehensive discussion of the renewed interest in bio-commodities follows, looking at drivers for this trend, types of agricultural and forestry resources, industrial applications and conversion technology. Special attention is given to lignocellulose as an abundant but largely undeveloped by-product from agriculture and forestry, biochemical conversion as one of the major technology platforms and ethanol, a bio-commodity with an already established market to which many research and commercial projects are dedicated.

2.1 Agro-industrial production as part of process industries

This section portraits the process industry which includes fuels and chemicals as well as agricultural and silvicultural production if a broad definition is applied.

2.1.1 Process industry characteristics

Fuel and chemicals production are part of the process industry. A production process point of view can distinguish process manufacturing, discrete manufacturing and energy conversion (Riebel 1963). While discrete manufacturing involves forming, shaping and assembling of materials, process manufacturing is concerned with converting materials into others using chemical, physical and biological processes (e.g. Vahrenkamp 2008: p. 86, Vauck and Müller 1999, Lynd et al. 1999). This allows for a classification of industries according to their dominating type of industrial processes and makes the process industry a distinct segment of manufacturing industries in general. Table 2.1 gives a list of process industry sectors and shows their number of employees and gross value added in 2010 in Germany.

Table 2.1 Process industry sectors and their employees and turnover in Germany

Branch	Employees[1]	Gross value added [Mill. EUR]	Turnover per employee[1] [EUR]
Food and forage products	799 314	29 586	185 092
Beverages and tobacco products	83 645	5 853	444 581
Paper and paper products	140 169	9 329	282 081
Coke and refined petroleum products	19 452	5 976	6 211 803
Chemicals and chemical products	324 371	36 650	460 685
Pharmaceutical products and preparations	114 683	15 436	351 246
Non-metallic mineral products	229 003	13 339	179 504
Basic metals	253 522	17 802	370 343
Total process industries	**1 964 159**	**133 971**	**341 223**

The overall economic importance of the process industry in Germany and Australia is highlighted in Table 2.2. Both countries are highly developed industrial countries. Australia is rich in natural resources and the mining industry dominates the economy so that the manufacturing sector does not contribute a high share of employees and gross value added. Within the manufacturing sector, process industries play an important role with about 50% of gross value added.

[1] Data for 2010 (Statistisches Bundesamt 2012)

Table 2.2 Economic relevance of the process industry in Germany and Australia

Process industry share of	Germany[1]	Australia[2]
employees in manufacturing [%]	28.4	41.9
gross value added in manufacturing [%]	29.4	49.9
employees in whole economy [%]	7.8	3.7
gross value added in whole economy [%]	10.3	3.9

Easy access to commodities has shaped the manufacturing sector towards processing these into food, base metals and chemicals. But an economy that is scarcely endowed with economically exploitable natural resources can also have a strong process industry, which the case of Germany shows with a process industry share of slightly more than 10% gross value added of the whole economy.

International trade allows process industries to operate production facilities in a country like Germany far away from the raw material sources they rely upon. Other examples are the process industries of Singapore and Japan which also rely heavily on imported raw materials (Carpenter and Ng 2013, PAJ 2014).

Energy generation is not classified as a process industry in Table 2.1, since it plays a distinctive role and is not included among process industries in most statistics. Firstly, there is also energy generation without chemical conversion (e.g. hydro power), and energy itself unlike other chemical industry products is an intangible good. However, a significant share of global energy demand is supplied through chemical conversion processes, and energy carriers such as solid, liquid and gaseous fuels are products that deliver chemical energy. Therefore, production of fuel products can be regarded as one of the most important process industries that shares many characteristics, structures and links with the actual chemical industry.

[2] Data for 2009-2010 (ABS 2012)

While the degree of **internationalisation** varies between branches of the process industry, another difference is highlighted in Table 2.1. The coke and refined petroleum products industry is highly capital intensive, with a turnover per employee more than thirty times as high as in the food industry. Another measure of **capital intensity** is the value of assets per employee. In this measure, petroleum refining is surpassed by mining and energy generation only. Other process industries like chemicals and pharmaceuticals have comparatively high values as well, whereas food production is characterised by relatively low values of assets per employee (Couper 2003: p. 56). Depending on the branch, capital investments play an important role and have to be adequately considered in every economic analysis.

Another characteristic of the process industry is a **diverging production structure**, i.e. several products are produced from few raw materials, in contrast to car manufacturing for instance, where millions of parts are assembled to produce a single product (Günther and Tempelmeier 2005: p. 19). Also typical is that process industries often carry out the first conversion steps after raw material sourcing. This property is vertical **proximity to raw material origins** from natural processes or mining operations (Hirth et al. 2007). Process industries do not necessarily require a geographical proximity, as explained above for Germany. Raw materials itself and products with vertical proximity to raw materials are often **commodities** which are produced at standard qualities in high volumes for spot and contract world markets (Geman 2005). Vertical proximity to raw materials does not mean that process industries do not produce end-products. Since the beginning of the industrial age, a complex network of products and processes has evolved in the process industries ranging from raw materials to intermediates, specialities and consumer products with applications for food, materials and energy.

A high **level of integration** is typical especially for the fuel and chemical industry, where the processing of multiple feedstocks into multiple products is often realised in large refineries and chemical parks or *verbund* locations (Höchst et al. 2010). The fuel and chemical industry handles dry bulk, liquids and gases as raw materials and products, applies continuous or batch-mode conversion processes and features a diverging production structure, i.e., the number of end-products is higher than the number of raw materials (Schürbüscher et al. 1992). Many chemical, physical and biological conversions can be carried out by fundamental unit operations, which enables the use of similar equipment for different processes (see e.g. Vauck and Müller 1999, Chmiel 2005).

Apart from some notable exceptions like liquefied petroleum gas, gas-to-liquid (GtL) and coal-to-liquid processes (CtL, e.g. petrol produced from coal on a larger scale in South Africa, Güttel et al. 2007), liquid fossil fuels are based on petroleum (crude oil). The petroleum industry supply chain is traditionally split into upstream, midstream and downstream operations (An et al. 2011b). Upstream operations consist of exploration (drilling) for petroleum, extraction of petroleum from the source and transportation to further processing. High volumes of petroleum are generally extractable from single wells. Midstream operations, sometimes grouped together with downstream operations, refine crude oil into various products. Downstream operations proper comprise storage and distribution to end customers of transportation fuels and also represent the link to all petrochemical derivatisation based on petroleum products like naphtha as a feedstock. Transportation fuel markets include passenger cars, commercial road vehicles, rail, aviation and marine fuels, as well as niche markets like fuels for chain saws and horticultural devices. These fuels are standardised bulk products demanded virtually everywhere around the world. As pumpable, high-energy density liquids, petroleum feedstock as well as petroleum products are transported in high quantities through pipelines and tankers.

Summarising, the fuel and petrochemical sectors are process industries with similar production technology and structure. They are characterised by internationalisation, large scale, capital intensive operations, high levels of integration, vertical proximity to raw material origins, commodity products, diverging production structure and high volume markets. Agricultural raw materials are used in the food industry. Petroleum feedstock is the main pillar of the chemical and fuel industry but alternative feedstock sources are becoming increasingly important.

2.1.2 Agricultural and forestry production

The primary sector of the economy can also be regarded as a process industry in the broadest sense, as agricultural and forestry growing processes are ultimately biochemical conversions. It is typically considered a separate fundamental sector of the economy because of its unique organisational and operational features. The commercial production of wood conducted by forestry businesses is relatively integrated regarding supply chain ownership and industrial use of wood and wood products like furniture manufacturing or pulp and paper production is common practice. In some countries and regions there are small-scale forest owners and harvesting operators, but commercial forests and plantations are more often owned by large companies that run an integrated supply chain encompassing growing, harvesting and processing operations. Farming on the other hand is often conducted by several organisationally independent small-scale operators. Average farm size and the scale of farming operations varies with the farming activities carried out as well as with countries and regions.

Farmers often produce for an anonymous commodity market. Agribusinesses conduct handling, storage and primary processing operations and provide the link to further processing of agricultural goods in the food and beverage industry. Apart from these organisational features, the agricultural as well as the forestry sector are also characterised by the properties of biological resources which are exposed to the changing conditions of the natural environment in which they are grown (see section 2.2.3).

If agricultural biomass is used as a raw material for industrial production, operations of the primary sector have to be integrated with operations of the industry that converts the feedstocks into value-added products. This leads to integrated supply chains that may be consequently referred to as *agro-industrial supply chains*. The Oxford Dictionary defines an 'agro-industry' as an

> "Industry connected with agriculture" or as "Agriculture developed along industrial lines" (Oxford Dictionaries 2014).

The concept is already known in traditional agribusiness, where food and beverage industries are connected with agricultural production of raw materials or where agriculture is carried out by large integrated organisations managed as industrial enterprises, similar to large-scale forestry operations.

Fittingly, commodities for the fuel, electricity, chemicals or materials industries produced from agricultural or forestry resources are referred to as *bio-commodities*. These new bio-commodities join the traditional bio-commodities of the food and wood industries, such as sucrose sugar, cocoa butter, vegetable oil or pulp. The term has been in use at least since the mid-1990s amid the emerging interest in industrial use of renewable raw materials (see e.g. Lynd 1996 and Lynd et al. 1999 for early use in this context). It has also been used to distinguish renewable 'biocommodities' from unrenewable 'geocommodities' (Floyd 1993).

2.1.3 Supply chains for bio-commodity production

An agro-industrial supply chain can be split into the following five fundamental elements: feedstock provision, pre-processing, conversion into final or intermediate products, end-use and logistics. While elements can be named differently in the literature, other authors effectively aggregate supply chain operations similarly to the categories shown in Figure 2.1 (e.g. O'Connell and Haritos 2010).

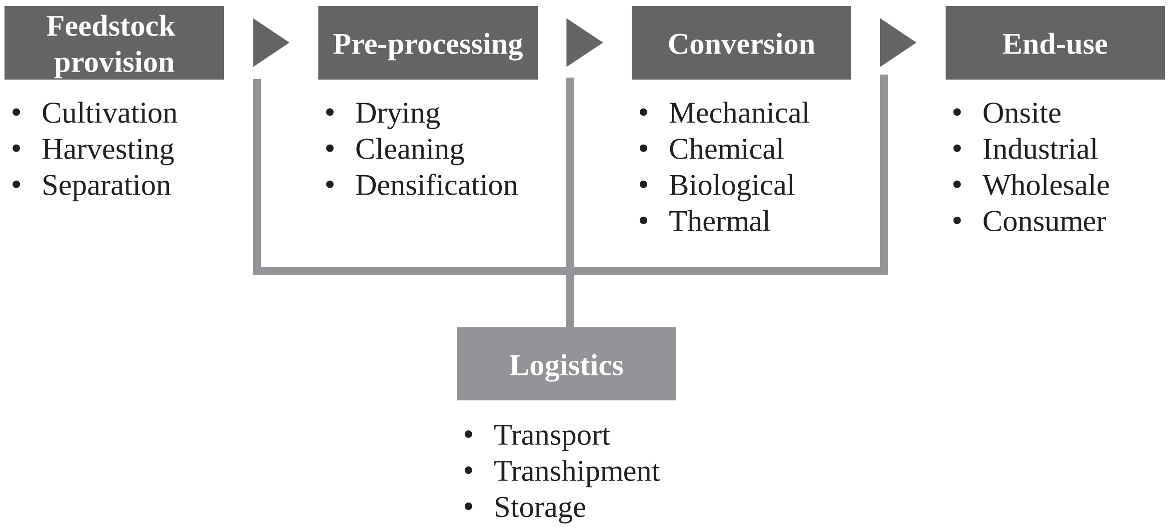

Figure 2.1 Agro-industrial supply chain elements

Feedstocks are provided by agricultural or silvicultural production systems, and can be a main or a by-product. In crop farming, feedstock provision begins with cultivation of a crop on a field. Cultivation processes include tillage, crop protection, fertiliser application and sowing. The crop is then harvested mechanically or by hand, often annually (e.g. most grains, sugar cane) but in some cases also every two years (e.g. sugar beet) or in other patterns. Separation of different crop products, for instance grain seed and straw, can be done in one step with harvesting (using a combine harvester) or in single steps. As agro-industrial supply chains can also start with by-products as primary raw