Bioenergy development pathways for Europe
Potentials, costs and environmental impacts

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Potentiëlen, kosten en milieu-impacts

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Abbreviations and Units

AEZ	Agro Ecological Zoning
BTL	Biomass to liquids
$CaCO_3$	Limestone
$CaMg(CO_3)_2)$	Dolomite
CAP	Common Agricultural Policy
CEEC	Central and Eastern European Countries
CH_4	Methane
CHP(s)	Combined heat and power (systems)
CO_2	Carbon dioxide (Carbonic oxide)
CO_2-eq.	CO_2 equivalent (refers to the GWP of gases relative to that of CO_2)
CTL	Coal to liquids
DME	DiMethylEther
EC	European Commission (Commission of the European Communities)
ECSC	European Coal and Steel Community
EEA	European Energy Agency
EEC	European Economic Community
EJ	Exa Joule (10^{18} Joule)
ETS	Emission Trading Scheme
EU	European Union
FAO	Food and Agricultural Organisation (of the United Nations, UN)
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information System
GJ	Giga Joule (10^9 Joule)
GTL	Gas to liquids
GWP	Global Warming Potential
IEA	International Energy Agency
iLUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
K_2O	Potassium oxide
LE	Lignocellulose Ethanol
LHV	Lower Heating Value
LUC	Land Use Change
MFP	Multi factor productivity (analysis)
MJ	Mega Joule (10^6 Joule)
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_3	Nitrate
NREAPs	National renewable action plans
NUTS	Nomenclature of Units for Territorial Statistics
P_2O_5	Phosphorus pentoxide
PJ	Peta Joule (10^{15} Joule)
ppm	Parts per million
PR	Progress ratio
RED	Renewable Energy Directive
SFF	Sacharification and Fermentation
SNG	Substitute Natural Gas
SOC	Soil Organic Carbon
SRC	Short Rotation Crops
UN	United Nations
WEC	Western European Countries

1 Introduction

1.1 Towards a sustainable energy system: the role of bioenergy

Fossil dominance and future production shifts. Fossil resources dominate the global energy system, supplying more than 85% of the nearly 500 EJ primary energy used every year (IPCC, 2011). Petroleum (oil) is used for more than eighty percent for transport fuels and as a raw material for plastics and chemical products. The most significant uses for coal are in electricity generation, steel production and cement manufacturing (WCO, 2011). Primary uses for natural gas are in electricity generation, domestic uses including cooking and heating and in the industry e.g. as a major feedstock for ammonia production for nitrogen based fertilizers. One shift in the fossil fuel mix is an increase in the use of natural gas to displace coal based power production which offers an affordable and fast route to lower CO_2 emissions (IEA, 2011). Dominant reliance on fossil fuels cannot be sustained in the long run for several reasons. Firstly, because fossil resources are *a priori* finite. Secondly, increasing scarcity of (affordable) fossil resources and an uneven distribution of resources globally may have (geo)political and strategic consequences. Thirdly, when (affordable) fossil fuel supplies fail to meet demand this can increase price volatility, cause price spikes and even permanent higher price plateaus. When sustained for longer periods this may stall economic growth or lead to economic contraction. Fourthly, the gradual but substantial increase of fossil fuel use has led to a rise in anthropogenic carbon dioxide (CO_2) emissions and as a result in higher atmospheric CO_2 concentrations with implications to the earth's climate.

Greenhouse gas emissions, the (enhanced) greenhouse effect and climatic change. Greenhouse gases are emitted to the atmosphere through various natural occurrences and human activities. With regards to anthropogenic sources, the highest contribution comes from carbon dioxide (CO_2) emissions from the combustion of hydrocarbons, deforestation and organic decay, followed by methane (CH_4) emissions from enteric fermentation and manure from animal husbandry and nitrous oxide (N_2O) emissions from fertilizer use. Greenhouse gases have the ability to trap heat radiated from the earth's surface, keeping temperatures on earth fairly constant. Increasing anthropogenic GHG emissions raise atmospheric CO_2 concentrations and thus global mean temperatures (Arrhenius, 1896). Although a direct relation between anthropogenic greenhouse gases and observed climatic change is difficult to prove due to complexity of the earth's system, the Intergovernmental Panel on Climate Change (IPCC), in its fourth assessment report in 2007, concluded that *"Most of the observed increase in global average temperature since the mid 20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations"* (IPCC, 2007). By the end of 2010, CO_2 concentrations had increased to 390 parts per million (ppm), a 39% increase compared to pre-industrial levels of 280 ppm. To reduce the risks associated with climate change most nations have agreed to set reduction targets and deploy actions to prevent the global mean temperature from rising by more than 2 °C above pre-industrial levels (UNFCCC, 2009). To achieve this goal climate models suggest that atmospheric carbon dioxide concentrations should be limited to 450 ppm, although considerable uncertainty surrounds this figure (Meinshausen, 2006). Climate change already leads to, and potentially accelerates, adverse impacts such as more extreme weather both leading to an expansion of areas affected by drought as well as local distortions of the hydrological cycle. Especially worrisome in this respect are climate change 'tipping points', non-linear transitions where small forcing can make a big difference, such as the irreversible melt of the Greenland ice sheet and the change of ocean currents (Lenton and Schellnhuber, 2007).

Curbing GHG emissions: accelerating bioenergy use. Energy related GHG emissions can be reduced by increasing energy efficiency, nuclear energy, carbon capture and storage and renewable energy. From the renewable energy technologies like solar and wind energy; bioenergy contributes nearly 80%. In 2008, global primary biomass production for energy was 50 EJ, mostly traditional biomass referring to the use of wood, charcoal and agricultural residues in developing countries. Modern biomass applications contributed 12.4 EJ; largely residues, wastes, and forest biomass for heat and power and agricultural crops. The IPCC projects primary biomass for energy supply to increase from 50 EJ to 80 EJ in 2030 and 138 EJ in 2050. In addition to these median figures, upper estimates of 150 EJ in 2030 and 300 EJ in 2050 are given for global biomass supply (IPCC, 2011). The contribution of traditional biomass is expected to decline while modern bioenergy will contribute more as a result of industrial investments and government goals. In Europe, environmental and biofuel policies (Commission of the European Communities, 2009) have accelerated bioenergy consumption in the past decade, which is met by a combination of imports and domestic production. Between 2005 and 2010, Europe's total primary energy production from biomass increased by 53%, from 3.0 to 4.6 EJ y^{-1}. This value is expected to grow to 6.2 EJ y^{-1} by 2020 according to the national renewable action plans (NREAPs) (EurObserv'ER, 2007; EurObserv'ER, 2010). As a consequence of surging demand and a mismatch between demand and supply regions, biomass for energy is increasingly traded internationally, both as feedstock (e.g. wood pellets) and as fuel (e.g. bioethanol) (Junginger et al., 2008). Europe at present is a large importer of solid and liquid biofuels (Junginger et al., 2011).

Bioenergy: feedstocks and technologies. Bioenergy refers to a wide range of biobased feedstocks and technologies. Common biomass feedstocks include residual streams from forestry, agriculture, dedicated production by annual or perennial energy crops, and other biomass waste streams such as the organic fraction of municipal waste. Bioenergy technologies produce power or heat directly, or create gaseous, liquid or solid fuels from biomass feedstocks. The range of bioenergy technologies is broad and their current use and technical maturity variable. Among the technologies and feedstocks that dominate modern bioenergy use at present are the co-firing of wood pellets in coal-fired power plants, wood chip and wood pellet based heating systems, and first generation biofuels for transport: ethanol produced from sugar and starch crops such as corn, sugarcane and sugar beet, and biodiesel produced from soy and rapeseed. Technologies that are making their market entrance are biofuels produced from lignocellulose-feedstocks (referred to as second generation biofuels) and advanced power generation through gasification (IPCC, 2011).

Bioenergy benefits. Several benefits of bioenergy drive its (increasing) use. Firstly, bioenergy can substitute fossil fuels, including oil, the resource most short in global reserves and expensive. Many governments aim to increase the use of biofuels in particular for energy security reasons. Secondly, bioenergy avoids GHG emissions by replacing fossil energy, provided it is produced sustainably. In particular, biofuels can be applied in transport, a sector that has very few GHG mitigation options for the near term. Thirdly, biomass resources are produced around the globe, which offers economic opportunities for trade and can increase a country's energy self-sufficiency. Fourthly, biomass feedstocks can be integrated in many existing energy infrastructures for power and heat and many applications are cost-effective. Biofuels can directly replace gasoline and diesel and thus mineral oil. Fifthly, cultivation of energy crops can offer economic opportunities to farmers and farming communities, stimulating rural development. Lastly, biomass is the only renewable resource that can be deployed as feedstock in materials and chemicals production. Moreover, integrated (bio-refinery) concepts can deploy cascading chains, improving resource efficiency and potentially reducing GHG emissions .

Bioenergy drawbacks: preconditions for sustainabale bioenergy use. With the recent rapid increase of modern bioenergy use globally, several drawbacks have become apparent that need to be addressed to secure sustainable deployment. The use of biomass for energy can lead to changing land use patterns, deforestation and unbalanced extraction of residues from agricultural and forest lands. In turn this can lead to negative ecological impacts, water stress, and biodiversity loss. Also, the competition for feedstocks and land between bioenergy and food can lead to undesired impacts. With the expected considerable increase of future bioenergy use, ensuring sustainable production is a key priority (van Dam et al., 2008). In response, legislation, standards, certification schemes and other initiatives are under development to address these issues. Dozens of systems and frameworks are under development by governments, NGOs and stakeholder initiatives, such as the various Roundtables. The Renewable Energy Directive of the European Commission explicitly addresses the sustainability issues of bioenergy and strongly rooted in it: for biofuels, meeting several sustainability criteria will be a prerequisite to be counting towards the obligatory target the directive contains (Faaij and Londo, 2010).

1.2 Crucial issues relating to bioenergy production in Europe

Europe plays an important role in the (further) development of bioenergy due to its ambitious renewable energy policies and its state-of-the-art agricultural sector. Over the past decades, Europe's agricultural output has increased significantly mainly from increasing productivities facilitated by a strong common agricultural policy (CAP). The main factors that necessitated past yield increases were population growth and a changing diet towards a higher average caloric intake. Now that Europe's population and diet stabilizes while yields keep rising, this creates opportunities to use European cropland for other uses, including bioenergy. The European commission in their renewable energy directive (RED) and rooted in this the biofuel directive, envision a large role for biomass resources to reach their 20% GHG mitigation target by 2020 (Commission of the European Communities, 2009). The rapidly increasing demand for biomass resources as a result of these policies combined with a limited domestic supply has increased the imports of solid and liquid biofuels in recent years. To assess the opportunities, limitations and implications of extended bioeenrgy use in a European context several crucial issues requires in-depth and integrated analysis. For example, further scrutiny is needed on the key driving forces that steer future biomass resource potentials and into the spatial distribution of these resources in Europe. The extent to which agricultural productivities can be increased, and the rate at which this can be established developed into key issues in the debate surrounding bioenergy potentials and need further assessment. Furthermore, there is a pressing need to further evaluate the specific environmental impacts associated with expanded bioenergy production. To assess the current economic performance of bioenegry options further, research is needed on the prospects of dedicated energy cropping systems and (advanced) bioenergy technologies to reduce future production costs. Related to improvements in this economic performance, the complex interactions between competing renewable or fossil technologies can be modeled to gain insight into technology diffusion patterns (market penetration). The background, existing literature and knowledge gaps relating to these issues are discussed in more detail.

European biomass resource base estimation. Estimates of the global technical potential of primary biomass resources vary from 0-1500 EJ y^{-1}. This range can be narrowed down to 200-500 EJ y^{-1} when taking into account issues that restrict this potential such as soil quality, water restrictions and the exclusion of protected areas (Dornburg et al., 2010). The European Union (EU) represents roughly 4% of global potentials (Smeets et al., 2007). This share roughly doubles when European countries east of the EU are included, such as Belarus, Ukraine, Turkey and Western Russia. This region has a close proximity to the EU and may therefore be of interest to supply biomass resources to EU markets (in the near future). To assess the technical potential of European biomass resources, various studies have been conducted, using different approaches delivering different outcomes. Earlier analysis of the biomass potential in nine central and Eastern European countries (CEEC) estimates a total 2-11.7 EJ y^{-1} for this region (van Dam et al., 2007). Another study, assessing biomass potentials for the EU15 plus the ten member states that joined the EU in 2004, Belarus and Ukraine, estimates a total of 17.2 EJ y^{-1} (Ericsson and Nilsson, 2006). The EEA estimates a primary biomass potential of ~12 EJ y^{-1} for the EU25 by 2030 that is 'environmentally compatible' (EEA, 2006). Common to these analyses is presentation of results on a country level. Key driving forces that determine the development potential of the European biomass resource base in these studies include: population, diet and aggregated food demand developments; the extent and rate at which food and livestock production can improve its efficiency, the net trade balance of Europe for food and animal feed products. The key driving forces mentioned that strongly influence future biomass resources potentials require much more detailed understanding because of the determining factor such as yield development are fixed on forehand by assumptions. have been identified to steer future biomass resource potentials. In particular, thorough assessment is needed of the future opportunities for crop-yield developments including an assessment of the preconditions that need to be satisfied to reach these levels. Furthermore, research is needed into the spatial distribution of biomass resources on a regional level. Such a regional distribution would particularly add insights for the larger European countries and countries that have an uneven distribution in their resource availability. This information could for example provide input to spatial transport models that analyze optimal routes between supply and demand regions.

Interactions with agricultural developments and food production. To accommodate the expected expansion of annual and perennial energy crops while sustaining food production at adequate levels, additional land can be brought into cultivation (expansion) or yields and efficiencies in conventional agriculture can be increased through augmented input levels (intensification) and improved management (rationalization). Specifically for Europe, possibilities to convert lands to agricultural use are limited making productivity increases the key factor to open-up biomass potentials. Assessments of the resource base use different projections for future developments in crop yields and in livestock production. The extent to which agricultural productivities can be increased, and the rate at which this can be established have become key issues in the debate surrounding bioenergy and biomaterial potentials. For example, studies performed for Europe, projected yield growth developments for the Western European countries between 0.8-1.5% y^{-1} and for central and Eastern European countries (CEEC) between 0.9-1.2% y^{-1} (FAO, 2003; Ewert et al., 2005; EEA, 2006).

Implications for the environment. Past agricultural intensification in Europe has effectively raised outputs, though not always by efficient use of resources and sometimes leading to negative environmental impacts. Developments include: increased fertilizer and pesticide use, professionalization of farmers, mechanisation, up-scaling of agricultural holdings and use of high-yielding varieties. Cropland expansion is associated with direct and indirect land-use changes ((i)LUC), such as the conversion of grasslands and fallow lands into cropland, leading to losses in soil carbon and thereby to GHG emissions. with its related emissions (Overmars et al.). If bioenergy is to be a viable option for mitigation of greenhouse gases (GHG), these upfront emissions will need to be more than offset within limited time with possible emission reductions due to fossil fuel replacement by biomass sources. If this is not achieved, this can lead to prolonged GHG payback times (Fargione et al., 2008; Searchinger et al., 2008; Al-Riffai et al., 2010; Lapola et al., 2010). As energy crop production on European croplands expands, driven by accelerating consumption of bioenergy, it is necessary to further evaluate the specific environmental impacts associated with this production. Several studies have used different approaches to evaluate the environmental impacts of increasing agricultural output. Whereas most of these studies focus on agriculture for food production only (Smith et al., 2000; Smith et al., 2008; Burney et al., 2009), some evaluate the effects of integrating biomass production into agriculture (Melillo et al., 2010). Advanced biofuels, produced from cellulosic sources, are recognised to offer advantages over biofuels production from annual (sugar, starch and oil) crops, including with respect to their GHG reduction performance (Luque et al., 2008; Arvizu, 2010). Issues that have not been addressed in these studies, requiring further investigation, are the implications for the environment that result from the combined implementation of adapted agricultural management, land use (and land cover) changes and expanded energy crop production. Aspects that are related to the environmental quality that need quantitative assessment include the total net greenhouse gas emissions (especially emissions of nitrous oxide and the net soil organic carbon fluxes) evaluation of changes to nitrogen and phosphorus surpluses in the soil that occur when they are leaked to the soil by leaching and runoff; changes to the (local) biodiversity; etc.

Economic performance and outlook for biomass feedstocks. Since the supplies of organic wastes, forestry and agricultural residues are limited, with increasing demand for biomass a larger share of the supplies will have to come from dedicated crop production. Apart from these lignocelluloses resources, demand is also increasing for feedstocks that can be used for the production of first generation biofuels such as sugar or starch based ethanol or vegetable oil based biodiesel. In Europe, this increasing demand is currently partly met by imports. Also, feedstocks produced in Europe are generally more expensive than imports. These elevated price levels are mainly caused by higher prices for land and labour and, specifically for perennial crops, due to the limited experience so far. Three recent studies show that significant cost reductions for agricultural crops for biofuels have been reached in cropping systems for US corn (Hettinga et al., 2009), Brazilian sugarcane (van den Wall Bake et al., 2009) and German rapeseed (Berghout, 2008). These studies found progress ratios, the rate at which production costs can be reduced with every cumulative doubling of established production, of 55, 68 and 80% respectively. Further research is needed to assess the prospects for dedicated energy cropping systems to raise production, gain experience and reduce production costs. In particular, perennial short rotation cropping systems require further assessment for example to evaluate to what extent experience curves can be applied to these systems.

Developments in bioenergy technologies. At present, (advanced) second generation biofuel technologies are pre-commercial. The production of lignocellulosic bioethanol comprises of pretreatment of the lignocellulose material, hydrolysis of the lignocellulose to break it down into sugars and fermentation of the sugars to convert it into bioethanol. The production of Fischer-Tropsch (FT) diesel comprises of the pre-treatment of the raw feedstock, gasification of lignocellulose material to syngas and FT-synthesis to diesel or other end-products like kerosene. Given that overall production costs for first generation biofuels are currently lower than for second generation fuels, the role of technological learning (and associated cost reductions) is a crucial factor affecting the possible market diffusion of, and competition between, first and second generation biofuel routes. More generally, further research is needed on experience curves to model the complex interactions between competing renewable and fossil technologies in order to gain insight into technology diffusion patterns . This can be used to model how resources are allocated to different end-use technologies over time, when optimized for specific parameters such as curbed GHG emissions, added value, least costs, *etc*

1.3 Aim and thesis outline

The main objective of this thesis is to evaluate development pathways for bioenergy in Europe by assessing preconditions for its development, an economic outlook for such development and an assessment of its environmental implications. Three main questions have been formulated addressing the knowledge gaps identified in the previous section:

1. What is the techno-economical biomass production potential in Europe, how is it spatially distributed and what driving forces steer its development over time?

2. To what extent can biomass potentials be realized sustainably in Europe without imposing adverse environmental impacts and conflicts with food production?

3. What are possible diffusion pathways of different competing biofuel production routes distinguished between developments in feedstock and conversion, given their current and future economic performance?

Table 1-1 Overview of the thesis chapters and the research question(s) addressed in them.

	Q1	Q2	Q3
Chapter 2: Biomass resource potential and costs	•	•	•
Chapter 3: Productivity developments in European agriculture	•	•	
Chapter 4: Environmental impacts of integrating biomass production into European agriculture		•	
Chapter 5: Learning in dedicated wood production systems			•
Chapter 6: Competition between biofuels	•		•

Chapter 2 addresses research questions 1 and 2 by assessing the European biomass resource potential and costs. Three methodological steps can be distinguished: (1) three scenarios (low, base and high) were constructed that project different growth rates for yield developments in European agriculture and as a consequence result in different land surpluses potentially available for energy crop production. (2) The modeled yields for 13 energy crops – based on Fischer *et al.* (2010) – were combined with the outcomes from step (1) to derive spatial biomass resource potentials in Europe. (3) For the same energy crops bottom-up costs were calculated applying national and regional cost factors to determine local cost levels in a spatially explicit way. Together these results were combined to construct cost-supply curves and maps for the regional biomass resource distribution in Europe.

Chapter 3 addresses research question 1 in more detail by assessing to what extent yield improvements can be realized in Europe in the coming decades and what the opportunities and relations are to biomass production potentials. The starting point for the analysis is the historic context of developments in European agriculture with regards to crop and animal production over the past five decades. An outlook is given on how yield levels could develop in Europe, what the preconditions for such developments and the implications for energy crop production in Europe are.

Chapter 4 addresses research question 3 by evaluating the environmental impacts associated with the expansion of energy crop production on European croplands driven by increased production of bioenergy crops. The approach simulates four key developments: (i) gradual intensification of agricultural production, (ii) gradual expansion of dedicated energy-crop production on cropland that has become available as a result of intensification, (iii) implementation of structural management improvements such as reduced tillage, fertilisation improvements and increased carbon inputs to the soil and (iv) the replacement of fossil fuels for transport with biofuels (see method section). For nine land-use combinations including agriculture and bioenergy crops, the chapter evaluates cumulative greenhouse gas emissions of N_2O, net organic carbon fluxes from the soil and abated emissions achieved by replacing fossil fuels for transport with biofuels.

Chapter 5 addresses research question 2 by assessing the learning potential of dedicated wood production systems to boost yields and reduce production costs. In particular, the chapter analyses past trends and provides a future outlook of developments in dedicated wood production for three cases: eucalyptus production in Brazil, poplar production in Italy and willow production in Sweden. A main objective of this chapter is to evaluate the extent to which experience curves can be devised for conventional woody plantation systems, and whether these can also be applied to SRC production systems.

Chapter 6 addresses research question 1 and 2 by modelling the diffusion of biomass-to-biofuel routes in the European biofuels market based on (relative) cost developments. An (endogenous) relation between cost development and cumulative production is constructed based on bottom-up insights and an experience curve approach. A combined scenario and sensitivity analysis evaluates the impact of variations in assumptions such as the 'timing of market introduction' and 'investment costs' on the market diffusion patterns of different biofuel routes.

Finally, **Chapter 7** summarizes and evaluates the findings from chapters 2 to 6, provides answers to the research questions, draws main conclusions and sets out recommendations for further research.

2 European biomass resource potentials and costs

Marc de Wit & André Faaij

Biomass and Bioenergy 34 (2010) p. 188-202

ABSTRACT The objective of this chapter is to assess the European (EU27$^+$ and Ukraine) cost and supply potential for biomass resources. Three methodological steps can be distinguished (i) an evaluation of the available 'surplus' land (ii) a modeled productivity and (iii) an economic assessment for 13 typical bioenergy crops. Results indicate that the total available land for bioenergy crop production – following a 'food first' paradigm – could amount to 900 000 km^2 by 2030. Three scenarios were constructed that take into account different development directions and rates of change, mainly for the agricultural productivity of food production. Feedstock supply of dedicated bioenergy crop estimates vary between 1.7–12.8 EJ y^{-1}. In addition, agricultural residues and forestry residues can potentially add to this 3.1–3.9 EJ y^{-1} and 1.4–5.4 EJ y^{-1} respectively. First generation feedstock supply is available at production costs of 5–15 € GJ^{-1} compared to 1.5–4.5 € GJ^{-1} for second generation feedstocks. Costs for agricultural residues are 1–7 € GJ^{-1} and forestry residues 2–4 € GJ^{-1}. Large variation exists in biomass production potential and costs between European regions, 280 (NUTS2) regions specified. Regions that stand out with respect to high potential and low costs are large parts of Poland, the Baltic States, Romania, Bulgaria and Ukraine. In Western Europe France, Spain and Italy are moderately attractive following the low cost high potential criterion.

Transport related primary energy demand in Europe is projected to increase from 11.7 to 16.1 EJ y^{-1} between 2000 and 2030. Transport thereby contributes to the European primary energy demand by a third (Commission of the European Communities, 2003). The European Union (EU) has set targets to curb transport related emissions while allowing for mobility to increase. It aims to establish this reduction by increased efficiency, i.e. by stimulating fuel efficiency for conventional drive trains, by encouraging penetration of (fuel and electricity) hybrid vehicles, by planning for the introduction of electric and hydrogen vehicles in the future and by the use of biofuels. The bio-fuel directive sets its first target to blend 5.75% of bio-based fuels with conventional gasoline and diesel for road transport by 2010 and 10% by 2020 (Commission of the European Communities, 2006).

Various studies have assessed the European biomass resources potential, with differences in scope, in approach and, consequently, in outcome (Hellmann and Verburg, ; EEA, 2006; Ericsson et al., 2006; van Dam et al., 2007). Production costs for biomass resources are assessed in the VIEWLS study (van Dam et al., 2007). Differences exist in the spatial coverage of the various studies. Ericsson & Nilsson (Ericsson et al., 2006) assess most countries, including the EU27 plus the large agricultural countries of Ukraine and Belarus. VIEWLS assesses seven Eastern European countries, selected for their assumed substantial supply potential. The EEA study (EEA, 2006) covers the EU25 (minus the three smallest EU states). Common to all the analyses is the use of statistical data and presentation of results on country level. This limits the opportunity of gaining insight into spatial differences between regions, especially within larger countries.

This study assesses the European cost and supply potential, covering the EU27 and Ukraine which has been explicitly included because of its vast potential and because of its neighboring location to the EU. Calculations for estimates on the supply potential of dedicated bioenergy crops are based on a land availability assessment and a detailed spatial one by one km grid-cell size yield modeling. Results have been aggregated over 280 European regions. For estimating crop production costs detailed bottom-up cost studies are used. When combined, this bottom up approach and high-level of spatial detail provides comprehensive insight into the important factors driving production costs. Scenarios are applied in order to explore how key variables impact on the supply potential and production costs of biomass resources. Agricultural productivity determines the land that is required to meet food demand. Consequently, gains with respect to this productivity determine, to a large extent, the amount of land that can be freed up for other land uses. The scenarios emphasize this crucial role of agricultural productivity and elaborate on drivers underlying the development of this productivity.

Three methodological steps can be distinguished. 1) An assessment is made of the land required for current and future land use for food and feed production. A key driver for changes in the food-related land claim is the rise in productivity that can be established in the future. For this variable, three scenarios are developed that project rates of change into the future for agricultural productivity and livestock production. Development speeds are differentiated between the Western European Countries (WEC) and the Central and Eastern European Countries (CEEC). The surplus land area potentially available for a dedicated bioenergy crop production is determined by this exercise. 2) A parametrisation of 13 bioenergy crops is coupled with an Agro Ecological Zoning (AEZ) database, providing information on soil characteristics and climate data. Data for the analysed crops are obtained from this spatially-explicit productivity (Fischer et al., 2010) 3) A bottom-up economic analysis is carried out to calculate the production costs of the assessed bioenergy crops. The cost calculation is based on data providing information on capital and miscellaneous costs, land costs, labour costs and fertilizer costs. These data are gathered from an extensive literature review. Following the scenarios, the development of labour and land cost are also hypothesized to increase with productivity increases.

The results, obtained from the three analysis steps enable the construction of cost-supply curves for the five analysed crop groups. Assuming different rates of development (according to the scenarios) for the key variables, especially the increase in productivity, we have obtained ranges around the base case values for both the supply and cost. In addition, the spatial detail of the results enables the construction of maps of Europe indicating the supply and costs for over 280 European regions. The outcomes of the study can provide insight into the spatial distribution of resources and can hence serve as an indication to identify promising (high-supply and low-cost) regions.

2.2 Methodology and inputs

2.2.1 Production potential for dedicated bioenergy crops

Land availability. Figure 2-1 provides an overview of the variables included for projecting how much land could become available for bioenergy crop production. The land available for biomass production is the residual land base after subtracting the land needed for food, feed and livestock, built areas, and set aside for nature conservation. The methodology applied is described in more detail elsewhere in this volume (Fischer et al., 2009). Key variables that steer projected changes in land area requirements include food demand (determined by population size and dietary habit), agricultural productivity and the self-sufficiency ratio of Europe.

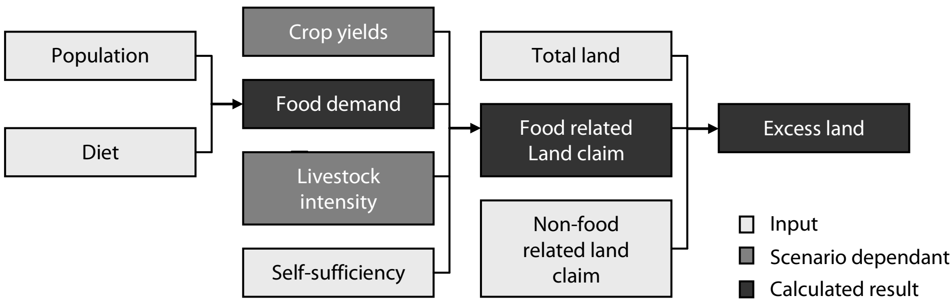


Figure 2-1 Schematic overview of variables that steer land use (change).

Both cultivated agricultural land and pasture is potentially considered for growing bioenergy crops, although more restrictions apply to the latter. For pastures to be used for crop production it requires conversion to arable land by tillage. Emissions related to tillage operations, depending on soil type and form of tillage can be considerable, thereby offsetting (part of) the emission reduction realized by applying biomass for energy use (Soussana et al., 2004).

The assessed time frame is from 2005 to 2030. An important assumption is that Europe will maintain its current (period 2000-02) level of self-sufficiency of around ninety percent for food and feed products. This thus entails that food demand and technological progress are key steering variables for freeing-up land. As food and feed production, nature conservation and built-up areas are allocated to the available land first, the resulting estimated surplus land can thus be interpreted as the available land without compromising food and feed production.

Scenarios and developments in agricultural productivity. Average European productivity of food crop production has increased significantly over the last five decades. The average increase differs sharply between the Western European Countries (WEC) and Central and Eastern European Countries (CEEC). In the WEC increasing fertilizer and pesticide use, more efficient farm management and up-scaling, have led to significant yield increases, especially since the 1960s and 1970s. In most world regions the rationale for increasing productivity levels was to secure food supply. In Europe this aim has been reached leading to self-sufficiency (Matson et al., 1997), to increasing exports and even to overproduction in some sectors (Lang et al., 2001). Grasslands have been freed up in the WEC as a result of two trends: increasing use of confined feed operations for livestock and dairy, and improvements in the caloric efficiency of feed conversion to animal protein.

Looking towards future developments in agriculture, the global trend is that of an increasing yield (FAO, 2006). Drivers underlying these increases are diverse, ranging from the increase of average farm sizes to pest and weed control to the optimizing of fertilizer use. To explore the bandwidth within which yield may develop, three scenarios are developed, illustrated schematically in Figure 2-2. As there are distinct differences in the observed rates of productivity development – for the period 1961-2005 – between the WEC and CEEC, we differentiate between these two regions in our scenario approach. For assumptions and scenario development on livestock productivity see analysis elsewhere in this volume (Fischer et al., 2009) .

Baseline scenario. While yields rose significantly between 1961-2005 in the WEC, in the CEEC there was only a modest increase. Under the baseline scenario for the WEC, yields are projected to increase at a constant rate continuing the historic trend.

For the CEEC the baseline trend is estimated to deviate upwards compared to the linear continuation of the observed trend. The rationale to hypothesize this upward trend is essentially twofold. First, a trend discontinuity for the CEEC is caused by the collapse of large-scale and fertilizer-intensive agricultural farming practices in the transition from centrally planned to market economies in the early 1990s (Turnock, 1996). This has induced a sharp fall in yield levels, illustrated by low yields per hectare in the post 1990 period. After this sharp decline the trend took an upward trend again. Simple trend extrapolation (for 1961–2005) would thus seriously underestimate the productivity growth potential that the CEEC could attain. Secondly, the accession of 12 CEEC countries to the EU will likely affect the development of the agricultural sector. By extension of the

EUs Common Agricultural Policy (CAP) and other policy support measures to the CEEC, it is expected that the CEEC and the WEC yields will converge by 2050. Developments that can contribute to this convergence are: access to capital for modernization and up-scaling and support for strengthening the social-economic rural situation. Figure 2-2 outlines the rapid increase in the rate of yield improvement in the CEEC.

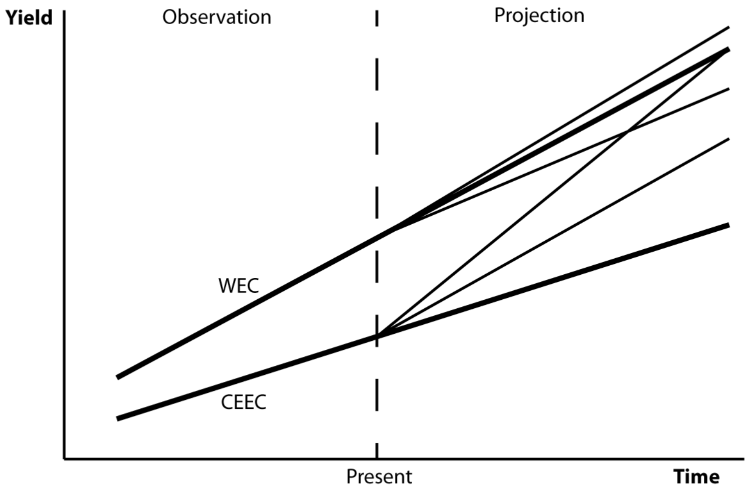


Figure 2-2 Schematic yield development scenarios (low, base and high) differentiated between the WEC and the CEEC.

Low estimate scenario. A low scenario is only considered for the WEC. The lower projection scenario for the WEC assumes an increasing share of arable land under organic farming management, a trend observed from the early 1990s (Willer and Yussefi, 2001; EUROSTAT, 2006). Organic farming is assumed to reduce average yields by between ten and thirty percent compared to conventional farming (FAO, 2003). In this study it is assumed that the average organic farming yield ‘penalty’ is twenty percent compared to the ‘standard’ farming practice. This scenario follows similar assumptions as studies that underline the importance of complying to strict sustainability criteria, e.g. (2006).

High estimate scenario. The high scenario assumes productivity increases for the WEC and the CEEC that exceed those under base case assumptions. For the CEEC the high scenario assumes that the ‘catching up’ of yields, driven by modernization of the agricultural sector, proceeds faster than what was assumed for the base case. Instead of catching up by 2050 (base case), the CEEC yields converge with the base case level of the WEC by 2030.

For the WEC yields are assumed to increase faster compared to the continuation of the historic trend (base case). This increased agricultural productivity can be attained by implementation of a multitude of measures that can be categorized by (i) measures that aim to increase efficiency by better management and (ii) measures that intervene in the plant’s characteristics by breeding optimization or genetic modifications. The first category includes among other things, wide-scale adoption of fertilizer, pest control – e.g

Integrated Pest Management (IPM) and Integrated Plant Nutrient Systems (IPNSs) –, irrigation optimization and farmer education (FAO, 2003). Moreover, policy steering aimed at farm size enlargement and crop specialization can be part of these measures.

The second category includes the breeding of High Yielding Varieties (HYVs) and the engineering of Genetically Modified Organisms (GMOs). In particular the use of GMOs is much disputed mainly because of the proliferation risk with indigenous and non-GMO crops. The global increase of the application of GMOs in agriculture, however, makes it likely that this option will become more widespread in Europe. In 2006 land worldwide under production with GMO crops exceeded one million km^2 globally (ISAAA, 2007).

2.2.2 Modelled bioenergy crop yields

Fischer *et al* .(Fischer et al., 2009) outlines the methodology used to compute the productivity for the assessed bioenergy crops. This entails the coupling of site-specific agro-ecological parameters (e.g. evaporation, irradiation, soil characteristics *etc.*) to crop specific growth parameterizations. The methodology provides the spatial distribution of the physical productivity for bioenergy crops on a one by one kilometer resolution. These detailed data are aggregated to NUTS2-level, to suit the aim of the analysis. Computations have delivered a database with the distribution of bioenergy crop yields for every NUTS2 region specified per (i) land suitability class and (ii) land use class. Five suitability levels are discerned, very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS) and not suitable (NS) (Fischer et al., 2009). Major land use classes include natural grassland (2), arable land (5), permanent crops (6), heterogeneous agriculture (7) and pastures (8) (EEA, 2007).

Supply potential. The physical production potential (PP) is calculated separately for arable land and grassland. To calculate the total physical production potential in a (NUTS2) region the average yield Y for a land suitability i (from VS to mS) and a land cover class l are multiplied by the land area A of the same suitability i and land cover class l, and subsequently added up for al suitability classes and land cover classes. Both the PP for arable land and for pasture includes all suitability classes, except NS. For the PP on pasture the natural grassland and pasture classes are included. For the PP on arable land, the LUCs arable land, permanent crops and heterogeneous agriculture are included.

$$PP_{pasture} = \Sigma\, Y_{i,l}\, A_{i,l} \qquad (2.1)$$

The physical production (PP) in the above equation is calculated for the whole (in this case NUTS2) region. To account for the fact that only part of the region is available for bioenergy crop production the physical production (PP) is multiplied by the regions estimation of the share of land (SAL) that is available for dedicated bioenergy crop production. The SAL depends on the scenario assumptions and is calculated following a (top-down statistical) land balance analysis (Fischer et al., 2009) . SAL comprises arable land and pasture that is potentially available for bioenergy crop production while food and feed demand are satisfied. The scenario approach applied here provides thus three values for SAL, which denote the available areas for bioenergy crops in total land area of the respective administrative region. In addition a caloric value (CV), based on lower heating values, is applied to convert physical production quantities to the energy of the crop group, see Table 2-1. For the crop groups of oil and sugar the physical production is also divided by, respectively, the extraction rate and the sugar content of dry matter. With this exercise we obtain the region-specific (NUTS2) energy production potential (EPP). The added subscript $_{N1}$ and $_{N2}$ denote whether applicable to a NUTS1 or NUTS2 administrative region.

$$EPP_{pasture,\,N2} = PP_{pasture,\,N2}\, SAL_{pasture,\,N1}\, CV \tag{2.2a}$$

$$EPP_{arable,\,N2} = PP_{arable,\,N2}\, SAL_{arable,\,N1}\, CV \tag{2.2b}$$

To compare the total yield between crop groups the physical quantities are converted into the energy quantities. The specific part of the harvested crop included in these figures is different between crop groups, see Table 2-1.

2.3 Production costs for dedicated bioenergy crops

Production cost analysis of the agricultural system for dedicated bioenergy crops is based on a literature review of crop-specific studies. Four major cost items are distinguished in the applied methodology land costs, labour costs, fertilizer costs and capital cost & miscellaneous. The three cost items capital cost & miscellaneous, labour costs and land costs are all given per unit of land (hectare based). Only the fertilizer costs are based on the realized yields (yield based).

The management level for production is considered to be the same over time and for all countries and is assumed to be of a high standard. This assumption also applies to regions where currently the management level for traditional food crop production is low. The rationale to apply this high level of management to all countries is that an important driver for a farmer to produce dedicated bioenergy crops is economical. Implicitly, however, the lower level of management, the general economic situation and the relative scarcity of land is reflected in the costs for labour and land. Therefore, the cost levels in the CEEC are generally lower than in the WEC. Figure 2-3 depicts a schematic representation of the agricultural production system its cost structure for capital goods, land, labour and fertilizer.

Land costs. The costs for land contribute significantly to overall production of agricultural products. Large differences exist in land rent prices, both within countries – between regions – as well as between European countries. Two major factors influence the cost for land, (i) soil suitability and (ii) the demand for land. A categorization for the first aspect of land suitability was already introduced in section 2.1.2. The demand for land is highly regionally dependant and therefore more difficult to assign to a specific plot of land. The land surface (A) of a certain suitability class (i) is denoted by A_i. A differentiation of land costs is based on Eurostat data (European Union, 2006). Land categories differ per country. Types that are generally discerned are arable, pasture, meadows *etc*. For all countries three levels of land rents are derived, denoted by price P for land type i. Although these categories, for suitability and cost of the land, refer to different aspects of the land, they are combined in the analysis. In total, five classes are defined for the land suitability and three for the price level of the land (see Table 2-2). The highest land price level is coupled to the best suitable (VS) land, the second highest price level to the suitable (S) land and the lowest price level is coupled to the three lowest suitable land types (MS, mS and vmS).

$$CT = CC + CL + C_{lab} + CF \tag{2.3}$$

Table 2-1 The caloric values (on LHV basis) for the assessed crops. When applicable the crop composition or extraction rate is given (ECN, 2006).

Crop groups	Crops	Caloric value[a] *GJ_{LHV} product^{-1}*	Composition
Lignocellulosic crops	Poplar Willow Eucalyptus	18,4 GJ (tonne of crop)$^{-1}$	The harvest index does not apply to (herbaceous) lignocellulosic crops. The whole crop is considered for energy purposes.
Herbaceous lignocellulosic crops	Miscanthus Switchgrass Reed canary grass	17,8 GJ (tonne of crop)$^{-1}$	
Oil crops	Sunflower	24,4 GJ (tonne of oil)$^{-1}$	44% Extraction rate[b] (seed to oil)
	Rapeseed		40% Extraction rate[b] (seed to oil)
Sugar crops	Sugar beet	17,3 GJ (tonne of sugar)$^{-1}$	75% moisture 15% sugar 10% rest of plant
Starch crops	Wheat Rye Triticale Corn	16,3 GJ (tonne of grain)$^{-1}$	A general harvest index for grains (starch crops) of 0,31 is used, above ground biomass to grain (Kemanian et al., 2007).

NB – Lignocellulosic and herbaceous lignocellulosic crops are in whole plant yields in tonne (dry), requiring only a conversion to energy units by applying the caloric value. Results of sugarbeet yields from the agro-ecological attainable yield assessment are given in kg sugar ha^{-1}. The dry weight composition of sugar beet is 60% sugar and 40% other constituents (protein, lignin *et cetera*). The sugar yield divided by the share of sugar gives the total crop yield. This yield is multiplied with the caloric value of sugar (this overestimates the energy yield slightly because most other constituents have lower caloric values). Similarly, oil crops are stated in (kg oil) ha^{-1}. With an average extraction rate (of the seed to the oil) the seed harvest is calculated by dividing the oil yield by the extraction factor. The yield is multiplied with the caloric value of oil.

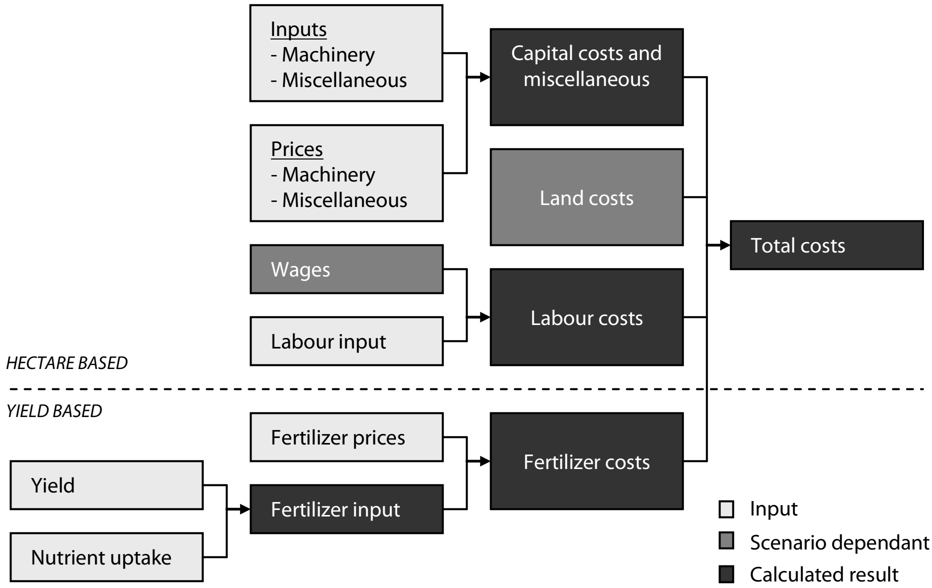


Figure 2-3 Schematic overview of cost factors in the agricultural production system.

Development in land costs. The approach, explained in paragraph 2.2.1, asserts that, induced by the accession of the CEEC to the EU, agricultural productivity could rise due to a higher availability of agricultural funds from the EU. This can be expected to induce modernization of the agricultural sector and improve the general economic situation. Ultimately this will affect land (rental) prices. To account for this increase a time dependant *land cost factor* is introduced that over time lets land prices rise according to one of the three scenarios (equation 5). In the base year the cost difference between land cost in the CEEC and the WEC is significant, with average land cost in the WEC at 253 € ha^{-1} y^{-1} compared to 52 € ha^{-1} y^{-1} in the CEEC. For the low scenario no increase is assumed to take place over time. For both the base and high scenario the land rent prices in the CEEC will increase between 2005 and 2030 from the CEEC average to the WEC average. This convergence results in an land rent increase of 489% over 25 years, or an increase of about 8 € ha^{-1} y^{-1}.

$$CL = LCM\,([\Sigma\, P_i\, A_i]/A) \text{ for } i=1,3 \qquad (2.4)$$

$$LCM = [(CL_{WEC,o} - CL_{CEEC,o})/T]\, t + CL_{CEEC,o} \text{ for } t=0,T \qquad (2.5)$$

Table 2-2 Cost overview for wages, fertilizer prices and land costs.

Country	Wages[a]	Fertilizer prices[b]			Land costs[c]		
		N	P_2O_5	K_2O	VS	S	MS
	€ h^{-1}	*€ (10^2 kg)$^{-1}$*			*€ ha^{-1} yr^{-1}*		
Austria	15,08	54	49	18	274	209	143
Belgium	16,51	54	49	36	203	197	191
Bulgaria	0,77	18	21	21	72	50	28
Cyprus	6,64	57	51	40	178	135	92
Czech Republic	3,87	23	12	17	72	50	28
Denmark	31,37	54	49	29	359	346	334
Estonia	3,80	29	24	17	72	50	27
Finland	16,73	54	49	33	164	113	62
France	9,52	56	51	37	137	132	127
Germany	14,13	45	51	35	267	258	248
Greece	4,61	44	49	33	512	389	266
Hungary	3,77	43	20	20	65	45	25
Italy	14,38	57	49	38	309	232	155
Ireland	17,72	54	49	33	196	189	182
Latvia	2,04	28	20	14	14	9	5
Lithuania	2,40	28	28	21	14	10	5
Luxembourg	13,99	53	49	34	174	168	162
Malta	5,38	54	49	33	178	135	92
The Netherlands	18,96	54	49	41	409	392	375
Norway	20,12	54	51	43	353	341	328
Poland	3,06	18	20	20	72	50	28
Portugal	4,76	46	49	34	178	135	92
Romania	1,09	18	21	21	72	50	27
Spain	14,38	28	20	20	180	137	94
Slovakia	3,06	28	20	20	14	10	5
Slovenia	7,81	47	47	30	14	10	5
Sweden	12,66	54	49	33	110	76	42
Switzerland	17,35	54	51	35	270	205	141
Ukraine	0,43	18	21	21	72	50	27
United Kingdom	14,42	68	47	32	208	201	194
Average WEC	*15,10*	*52*	*49*	*35*	*246*	*212*	*177*
Average CEEC	*2,92*	*27*	*24*	*21*	*50*	*35*	*19*

A – All data obtained from the LABORSTA (LABORSTA, 2006) database. Hourly wages are obtained as presented. If only monthly wages were stated an average of 160 working hours per month is assumed to calculate hourly wages. Wages stated are applicable to the agriculture, hunting and forestry sector.
B – Fertilizer prices are obtained from EUROSTAT (EUROSTAT, 2006) data. For the countries Bulgaria, Romania and Ukraine the price level of Poland is assumed since no data for these countries were found. For Switzerland the price level of Austria is used. For Norway the price level of Sweden is used.
C – Land cost calculation is explained in more detail in the section land cost development (2.2.1). Costs levels are presented for three suitability classes VS (very suitable), S (suitable) and MS (moderately suitable). For the countries Bulgaria, Estonia, Romania and Ukraine the price level of Poland is assumed. For Cyprus, Malta and Portugal the price level of Spain is assumed. For Latvia the price level of Lithuania is assumed. For Switzerland the price level of Austria is assumed.

Fertilizer input costs. Fertilizer costs are estimated by means of a nutrient balance methodology: nutrients taken up by the crop during its growth, including losses, must be replenished by fertilizers to maintain the soil's nutrient composition. Although this is an oversimplification compared to the actual practice – where over-fertilization or under-fertilization is common – it enables fair comparison of fertilizer requirement between crops and regions. In the analysis both annual and perennial cropping systems are compared with significantly different fertilizer requirements (Boehmel et al.) and, consequently, expenses for fertilization. The dry biomass yield (HC, harvested crop in t ha^{-1}) is taken as a starting point for the analysis. The crop-specific nutrient compositions (CC, crop composition in kg t^{-1}) for the three compounds Nitrogen, Phosphor and Potassium are multiplied with the biomass yield, resulting in the estimated nutrient quantities taken up from the soil during growth and harvest (USDA, 2006). Due to natural nitrogen deposition (D_N in (kg N) ha^{-1} y^{-1}), of which data are available on a country-specific level (Delbaere and Serradilla, 2004), the required nitrogen fertilizer application is less than indicated by the gross calculations. Furthermore, a nitrogen uptake factor (α) of 70% is applied to account for leakage (Biewinga and Bijl, 1996; Raun and Johnson, 1999) the remainder being sequestered by the soil. After correction for natural deposition and allowing for nutrient losses, the net input requirement of compounds is determined for the compounds Nitrogen (N), Phosphor (P) and Potassium (K). The fertilizer factor (FF), the ratio of fertilizer that has to be applied to compensate for the uptake of a certain compound is taken from USDA (2006), the factors being for nitrogen 1 kg N (kg N)$^{-1}$, for Potassium 1.21 kg K_2O (kg K)$^{-1}$ and for Phosphor 2.29 kg P_2O_5 (kg P)$^{-1}$. All Phosphor and Potassium supplied to the soil is considered to be taken up by the soil and by the plant during growth eventually. To calculate overall fertilizer cost, the physical input levels have to be coupled to fertilizer market prices (P_N, P_K and P_P in € (100 kg)$^{-1}$, see Table 2-2), including, respectively, nitrogen (N), di-potassium-oxide (K_2O) and di-phosphor-pentoxide (P_2O_5) (EUROSTAT, 2006).The described methodology is summarized in equation 6.

$$CF = HC\,[P_N\,FF_N\,(CC_N - \alpha\,D_n) + P_K\,FF_K\,CC_K\,P_p\,FF_p\,CC_p] \tag{2.6}$$

Labour costs. Labour costs are determined by crop-specific physical labour input requirements (h ha^{-1} y^{-1}) and by the hourly labour cost (wage is taken as a proxy for labour costs in € h^{-1}), based on country-specific values. Physical labour inputs are derived from various references (Mitchell et al., 1999; Bueren and Vincent, 2003; Pimentel and Patzek, 2005; Hagstrom, 2006; KTBL, 2006; Smeets, 2006; USDA, 2006; Monti et al., 2007). The country-specific labour costs for the agricultural sector are derived from LABORSTA (2006), see Table 2-2. The labour input intensity is affected by many aspects such as suitability of the soil (is a proxy for the attainable yield), management regime, level of mechanisation *etc*. These factors can vary significantly between countries, regions and farms. In the analysis only one value for the labour input is considered per crop (see Table 2-3) without differentiation with respect to any of the before mentioned aspects. The country-specific labour costs for the agricultural sector are derived from LABORSTA (2006), see Table 2-2.

$$CL = LI_i\,(W_j\,LM_{j,t}) \tag{2.7}$$

Where LI_i is the crop i specific labour input in h ha^{-1} y^{-1}, W_j is the country ($_j$) specific wage in the agricultural sector in € h^{-1}. The agricultural wage factor multiplier LM is country-specific and time-dependant. The increase of wages over time in the CEEC follows the same rationale as the development of land costs over time explained in section 2.4.1.. In short, Due to the accession of the CEEC to the EU wage levels are hypothesized to converge to or 'catch up' with WEC levels (European Commission (DG AGRI & DG EAE), 2006). The average wage in the CEEC increases from 2.9 € h^{-1} in 2005 to 15.1 € h^{-1} in 2030 (WEC average) for the baseline and high scenario. This corresponds to an increase of 0.38 € h^{-1} y^{-1} in wage for the CEEC, or more than a fivefold over 25 years.

Capital costs and miscellaneous. The capital costs and miscellaneous comprise primarily of expenses for machinery, the maintenance thereof and all cost items that are not covered by the other three cost categories. Table 2-3 provides an overview of the capital costs broken down according to three distinct phases in crop production (i) establishment and planting (ii) harvesting and field transport and (iii) storage and miscellaneous. For traditional (food) crops detailed references are available with respect to inputs into the production system, an overview is provided in Table 2-3. Costs for oil crops are specified for rape (KTBL, 2006) and sunflower (Pimentel and Patzek, 2005). For sugar crops only sugar beet is considered (Ali, 2004). Capital expenses for all starch crops are based on a study on wheat production (USDA, 2006).

Data on the production costs of perennial crops are scarcer than those for traditional crops and mostly refer to small-scale and experimental field trial data. Compared to conventional annual crops lignocellulose crops can be produced to relatively modest capital costs, mainly because these crops require an extensive farming practice. References for short rotation coppice are derived for poplar (Mitchell et al., 1999), willow (Hagstrom, 2006) and Eucalyptus (Bueren et al., 2003). References for the capital costs and misceleneous for perennial grasses are derived for Miscanthus (Smeets et al.), Switchgrass (Monti et al., 2007) and reed canary grass (Hagstrom, 2006). Expenses for herbaceous lignocellulose crops are at least for miscanthus and switchgrass almost three times as high as lignocellulose crops. This is mainly due to higher establishment costs, more frequent fertilization, herbicide and pesticide application and a higher harvesting frequency e.g. (Monti et al., 2007).

Cost reduction by learning in bioenergy crop production systems. Production cost estimates for the categories oil, sugar and starch are based on food production systems. The period assessed in the analysis is up until 2030. To account for learning effects responsible for decreasing costs, the results of a statistical analysis (described elsewhere in this volume (De Wit et al., 2009)) are applied to overall calculated production costs. Average overall learning effects on crop production costs over the assessed 25 year period are estimated to amount to between 16% and 37%. The effect on production costs is clearly illustrated in the cost supply curves, Figure 2-4.

Table 2-3 Overview of the (distribution of) capital expenses and labour input.

	Capital expenditure				**Labour**
	Establishment and planting	*Harvesting, field transport and storage*	*miscellaneous*	*total*	
		€ ha^{-1} yr^{-1}			*h ha^{-1} yr^{-1}*
Lignocellulosic crops					
Poplar[a]	94%	5%	0%	143	5,1
Willow[b]	76%	23%	1%	156	5,1
Eucalyptus[c]		*Not specified*		172	5,1
Herbaceous lignocellulosic crops					
Miscanthus[d]	36%	64%	0%	576	6,6
Switchgrass[e]	13%	84%	3%	512	9,7
Reed canary grass[f]	36%	58%	6%	194	10,6
Oil crops					
Rapeseed[g]	29%	68%	3%	292	7,2
Sunflower[h]	35%	65%	0%	290	8,6
Sugar crops					
Sugar beet[i]	38%	59%	3%	839	8,8
Starch crops[j]					
Wheat	47%	42%	11%	356	4,4
Rye	47%	42%	11%	356	4,4
Triticale		42%	11%	356	4,4
corn	47%	42%	11%	356	4,4

A – The cost for poplar cultivation is derived from Mitchell *et al.* (1999). The capital expenditure is dominated by the expense for plants and plantings, 57 € ha^{-1} yr^{-1} and the stool removal at the end of the plantation life time at 68,2 € ha^{-1} yr^{-1} and together responsible for more than 88% of total costs. Furthermore soil cultivation at 9,5 € ha^{-1} yr^{-1} and thinnings (cut back) at 6,8 € ha^{-1} yr^{-1} provide a significant contribution to overall costs. Other cost factors are loading, storage and transport (only local transport is considered here) only contributes marginally. Calculations consider a plantation rotation of 22 years (first year plantation set up and 21 years of production with 7 harvests) with a harvest every 3 years. For labour force estimate, see willow under [b].
B – The cost estimate for willow production is derived from Hagstrom (2006). Capital expenditures are dominated by the agriculture expenses at 134,15 € ha^{-1} yr^{-1}, comprising expendables (i.e. plants) and capital investment (farm equipment). The harvesting is the next large contribution with 19,52 € ha^{-1} yr^{-1} solely expenses for equipment and labour (as indicated below). Local transport at 2,20 € ha^{-1} yr^{-1} and communition at 0,42 € ha^{-1} yr^{-1} only contributes little. Labour hours required are stated in h ha^{-1} yr^{-1}. The labour build up for willow plantings comprises; agriculture (3,03 h ha^{-1} yr^{-1}), harvesting and field transport (1,36 h ha^{-1} yr^{-1}), road transport (0,58 h ha^{-1} yr^{-1}) and communition (0,14 h ha^{-1} yr^{-1}).
C – The cost for Eucalyptus production is derived from Bueren and Vincent (2003). After detailed discussion of plantation design and related cost factors they conclude with an average on farm production cost of 17,9 € $tonne^{-1}$ and an average yield of 12,6 $tonne^{-1}$. The labour intensity (again) is taken from Hagstrom (2006), amounting 5,11 h ha^{-1} yr^{-1}. To compensate for the cost for labour included in the on farm production cost the labour intensity assumed to an average wage (average US wage in agricultural sector 2005) at 10,57 € h^{-1} is subtracted.
D – (Smeets, 2006)
E – Cost for switchgrass are derived from a study by Monti *et al.* (2007). Monti et al. differentiate production cost according to three intensity scenarios; high, mild and low input and between two regions; north and south Italy. We assumed the mild scenario for Northern Italy to be the most comparable with other studies most. The study presents a very detailed overview of the cost aspects taken into account, differentiating between the establishment year and production years. The plantation useful lifetime is 15 years with production every year. For establishment the labour input is 13,0 h ha^{-1} yr^{-1} and 9,5 h ha^{-1} yr^{-1} in the production years, with an average of 9,7 h ha^{-1} yr^{-1}. The establishment year capital expenses are formed by fuel costs (69%), tractor cost (7%) and seed cost (5%) and other mostly farming equipment costs. Total cost

for the establishment year amount 1418,60 € h^{-1}. For the production years the distribution is somewhat different; fuels (63%), tractor (14%), herbicides (4%) and the rest made up by farming equipment. Total expenses in the production years are 447,32 € h^{-1} yr^{-1}.
F – Reed canary grass cost and labour input is derived from Hagstrom (2006). Capital expenses 194,16 € h^{-1} yr^{-1}. A (major) contributor to the expenses is baling, field transport and storage (52%), agriculture (36%), harvesting and field transport (6%), road transport (4%) and communnition (2%). Labour input is high (compared to other crops) at 10,59 h ha^{-1} yr^{-1} with the following distribution; baling, field transport and storage (55%), agriculture (26%), harvesting (9%), road transport (7%) and communition (3%).
G – Rapeseed costs are derived from KTBL (2006). Capital expenses amount to 292 € ha^{-1} yr^{-1}. Distribution of costs; (variable) machinery costs (51%), herbicide (21%), seeds (12%), fungizide (7%) and other cost factors (< 5%). Labour input is estimated at 7,2 h ha^{-1} yr^{-1}.
H – Sunflower cost are derived from Pimental and Patzek (2005). The capital expenses amount to 290 € ha^{-1} yr^{-1}. The distribution of the capital expenses includes; machinery (40%), (diesel) fuel (25%), transport (22%) and seeds (13%). The labour input is 8,6 h ha^{-1} yr^{-1} and is not specified further.
I – The capital cost estimate and labour force requirements are derived from a study by Ali (2004). The capital costs, which represent the highest capital expenditures per hectare per year for all crops considered in this study, are dominated by Machinery and related cost aspect expenditures. The capital recovery amounts to 288,19 € ha^{-1} yr^{-1}, related O&M costs are 84,94 € ha^{-1} yr^{-1} and the required fuel, lube and electricity costs amount 114,75 € ha^{-1} yr^{-1}; added together it is responsible for over 58% of total CAPEX. Additional costs comprise seed 86,02 € ha^{-1} yr^{-1} and custom operations 74,30 € ha^{-1} yr^{-1},
J – The capital expenditures estimates for starch crops are based on one study for corn by the USDA (2006). Expenses are dominated by the cost for seed 73 € ha^{-1} yr^{-1} , machinery and operating cost 121,43 € ha^{-1} yr^{-1}; repairs 30,43 € ha^{-1} yr^{-1} and fuel, lube and electricity 58,07 € ha^{-1} yr^{-1}. Labour contribution is not specified per specific task, at 4,41 (derived from cost for labour and average wage).

2.3.1 Forestry residues

The costs for forest (felling residue) biomass is dominated by transport costs from the forest collection site to an end or intermediate use site. The average biomass availability in relation to the distance between collection-site and end-use site is a function of the average forest density. Also the conversion plant scale influences the required supply distance. Based on all variables considered, Karjalainen derives a cost-supply curve for four countries; Poland, Finland, France and the Netherlands, indicating (on the cost-supply curve) the required production costs (i.e. gathering and field transport) to obtain the supply that can be 'harvested' within a 100 to 200 km radius.

To obtain a cost level for all countries, as an estimate for the cost of the forest felling residue resources, the marginal cost of chips for the four assessed countries are determined for a distance of 100 km. Data of these four countries are assumed to be (more or less) representative for the forest felling residue cost variety found in all European countries. The costs for Poland, Finland, France and the Netherlands are respectively 2.2, 2.8, 4.1 and 4.2 € GJ^{-1}. The overview presents country specific forest felling residues (Karjalainen et al., ; UN-ECE and FAO, 2000; Smeets and Faaij, 2007) and the sustainable harvestable amount of wood. Furthermore stems are included, not commonly used as a feedstock for fuel but used rather as timber and in the pulp and paper industry (Nyström and Cornland, 2003). There is, however, no fundamental reason why stem wood should not be used for fuel purposes. Stem wood is in fact, to some extent, used for energy purposes in Scandinavia and the Baltic region. The sustainable potential comprises the difference between the actual felling (stems) and felling residues (branches, leaves and other material) and the Net Annual Increment (NAI, an indicator for the annual forest growth). Wood volumes are converted to energy using the following conversion factors: average wood density 0.4 t m^{-3} and caloric value 18 GJ t^{-1}.

2.3.2 Agricultural residues

The supply potential for agricultural residues is taken from analysis explained elsewhere in this volume (Fischer et al., 2009). Essentially, two ratios are applied to annual country average food production statistics, yielding the net supply potential for agricultural residues.

The gross supply of agricultural residues arises from all residual streams (e.g. straw) obtained during production of food and feed, statistics are obtained from FAOSTAT (FAO, 2006). A sound agricultural practice requires that a part of the residues is left on the land (e.g. to maintain a healthy soil structure, enhance mineralization kinetics etc. (Griffiths et al., 2001)), the remainder can potentially be made available for energy applications. Residue figures are obtained by applying a crop-specific ratio of crop residue to crop main produce (RPR). Subsequently, a general residue use factor of 50% is applied to the food and feed production data to calculate the net availability. Although a fixed factor is applied several considerations can raise or lower this number (Wilhelm et al., 2004) depending on soil type, crop variety *etc*.

The production costs for agricultural residues stems from collection in the field, field transport and transport to an intermediate site or end-use site. No costs are allocated to production because agricultural residues are considered a residual stream from food production. A study by Allen *et al.* (Allen et al., 1996) estimates the total cost for straw (at plant gate) at between 2.1–3.3 € GJ^{-1}. Of these costs, transport contributes most at 31%, harvesting, chipping and baling accounts for another 24% together more than half of the cost. Handling of the biomass is still significant at 13%, while storage only contributes marginally at 4% (Allen et al., 1996). A study by the Joint Research Centre (JRC) (Edwards et al., 2005) estimates the costs (at plant gate) at 2.7 € GJ^{-1}. Cost data on agricultural residues used in this study are derived from the VIEWLS project (2004). The cost for agricultural residues is between 1.1–6.5 € GJ^{-1}.

2.4 Results

2.4.1 Biomass resources cost-supply potential

Dedicated bioenergy crop potential. Figure 2-4 shows six cost-supply curve graphs: five for each crop group and one summary figure for 2030. The cost-supply potential for the dedicated bioenergy crops is based on the available land, the crop-specific agro-ecological attainable yield (under rain-fed conditions) and the crop-specific production cost. The cost-supply curves are constructed for three reference years 2010, 2020 and 2030. The curves (the lines within the grey areas) indicate the baseline scenario for both the supply and the production cost estimates. The curves indicate the raw feedstock potential produced on 360 000 km^2 (2010), 530 000 km^2 (2020) and 660 000 km^2 (2030) arable land respectively and on 50 000 km^2 (2010), 140 000 km^2 (2020) and 240 000 km^2 (2030) of grass land (pasture and natural grassland). Bioenergy production on grassland is only considered for (herbaceous) lignocellulose crops, indicated with a dashed line. Around the curves the grey areas indicate the variation around the curves based on the low and high scenario on arable land. The numbers in the text between brackets indicate the ranges that correspond to the scenarios. Furthermore there is a decrease visible in the production cost for successive years, induced by learning of the agricultural production system (De Wit et al., 2009). Figure 2-7 shows the production costs on an area and energy basis for the five crop groups distinguishing between the WEC and the CEEC.

lignocellulose crops. The total supply potential for woody crops (poplar, willow and eucalyptus) on arable land for the years 2010, 2020 and 2030 amount to 4.4 EJ y^{-1} (4.2–5.6), 7.2 EJ y^{-1} (7.0–8.7) and 9.5 EJ y^{-1} (9.1–11.0) respectively. Production on grassland adds an additional supply (indicated with the dashed line) so that the total supply potential amounts to 5.9 EJ y^{-1} (5.7–7.6), 9.7 EJ y^{-1} (9.4–11.7) and 12.8 EJ y^{-1} (12.3–14.9), only baseline is shown in the graph. The curve shows a large initial supply potential (~ 60% of total supply) to relatively low cost, under 2.5 € GJ^{-1}, which is mostly concentrated in Central and Eastern Europe, dominated by willow cultivation, and some low cost production area's in Southern Europe, dominated by Eucalyptus cultivation. In addition to the low cost large supply regions some moderate regions supply (~ 30% of total supply) to moderate costs between 2.5 € GJ^{-1} and 4.0 € GJ^{-1}. At production costs higher than 4.0 € GJ^{-1} only a marginal supply (~ 10% of total supply) is available characterised by regions with high input costs or low productivity, and most often a combination of both. An overall, learning-induced production costs reduction of 20% (between 2005 and 2030) is applied.

Herbaceous lignocellulose crops. The total supply potential for herbaceous lignocellulose crops (miscanthus, switchgrass and reed canary grass) on arable land for the years 2010, 2020 and 2030 amounts to 5.8 EJ y^{-1} (5.7–7.6), 9.3 EJ y^{-1} (9.1–11.3) and 12.2 EJ y^{-1} (11.8–14.1) respectively. Grassland provides an additional potential so that the total of arable and grassland utilised amounts to 7.4 EJ y^{-1} (7.2–9.6), 12.1 EJ y^{-1} (11.8–14.7) and 15.8 EJ y^{-1} (15.3–18.4). The curve shows a steady increase of supply (~ 40% of total supply) toward a cost level of 3.5 € GJ^{-1}. At relative moderate production cost levels between 3.5 € GJ^{-1} and 4.5 € GJ^{-1} a significant supply potential (~ 30% of total supply) is available. At costs higher than 4.5 € GJ^{-1}, which can be considered very high, a large additional supply is available (~ 30% of total supply). A 20% production cost decrease is observed for learning.

Oil crops. The total supply potential for oil crops in oil (rapeseed and sunflower) for the years 2010, 2020 and 2030 amounts to 1.7 EJ y^{-1} (1.6–2.2), 2.6 EJ y^{-1} (2.5–3.2) and 3.3 EJ y^{-1} (3.2–4.0) respectively. A considerable supply potential (~ 45% of total supply) is available for under 6.0 € GJ^{-1}. From 6.0 € GJ^{-1} the costs increase sharply to stall at around 10.0 € GJ^{-1}, representing a moderate supply potential (~ 30% of total supply). Only a small fraction of the supply potential (~ 15% of total supply) is available with production costs exceeding 10.0 € GJ^{-1}. Note that fertilizer costs are only allocated to the (mass) fraction of the seed produced – excluding that of straw and other residue streams –,but, however, included in that of seedcake (a residue from oil extraction). Production costs reduce by 16.3% over the assessed period (2005–2030).

Sugar crops. The total supply potential for sugar for the years 2010, 2020 and 2030 amounts to 2.9 EJ y^{-1} (2.8–3.8), 4.6 EJ y^{-1} (4.4–5.7) and 6.0 EJ y^{-1} (5.7–7.1) respectively. The cost supply path shows a steady increase. A large supply potential is available (~ 60% of total supply) for production costs under 6.0 € GJ^{-1}.f total supply) is available.

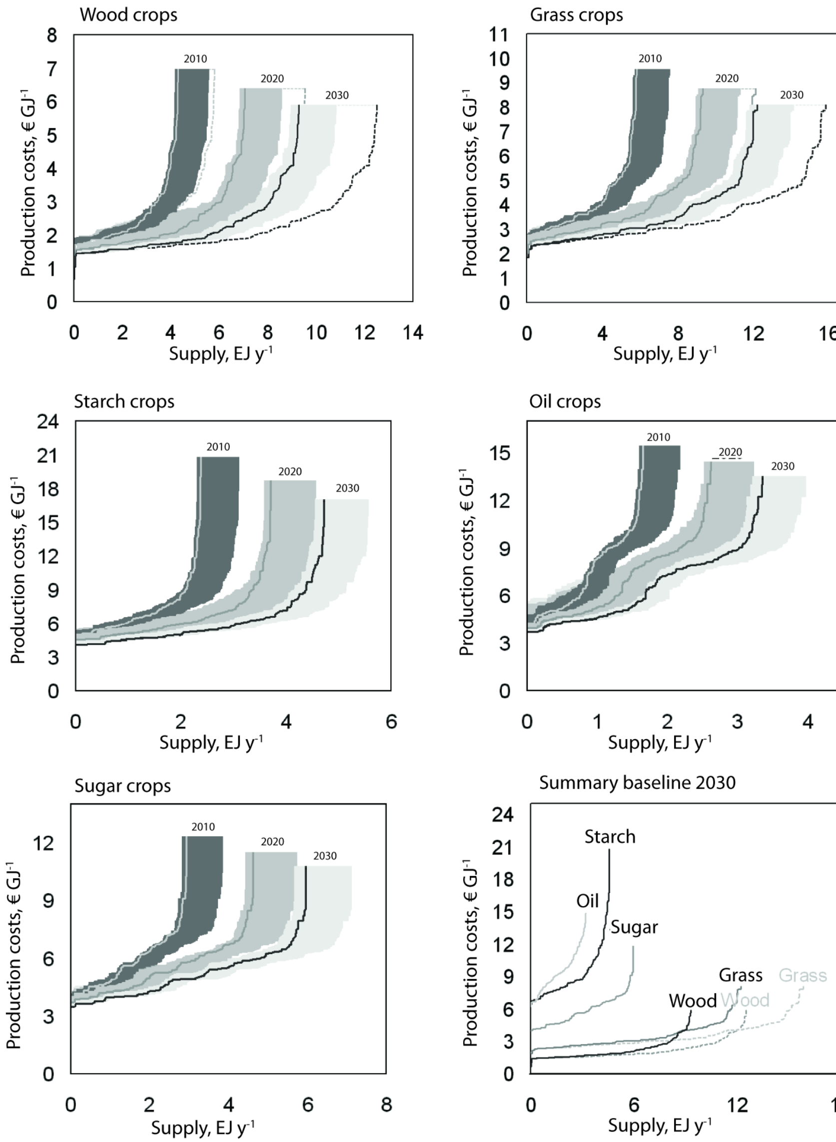


Figure 2-4 Cost-supply curves for five assessed crop groups. The summary figure depicts cost-supply for all crop groups for the 2030 curves for the baseline scenario.

At costs above 7.5 € GJ^{-1} a marginal supply (~ 10% of total supply) is available. Learning-induced production cost decrease amounts to 16.5%.

Starch crops. The total supply of starch from cereal and coarse grains (wheat, barley, rye, maize and sorghum) for the years 2010, 2020 and 2030 amounts to 2.4 EJ y^{-1} (2.3–3.1), 3.7 EJ y^{-1} (3.6–4.6) and 4.7 EJ y^{-1} (4.5–5.6) respectively. Under 7.0 € GJ^{-1} a large supply potential (~ 60% of total supply) is available. A moderate supply is available (~ 20% of total supply) between 7.0 € GJ^{-1} and 8.5 € GJ^{-1}. Production costs decrease with 24.7% over a 25 year period.

The energy supply potentials of each of the resource classes, does not predict the energy potential of the resulting biofuels since each class has a different conversion efficiency and capital and operating cost structure. The supply curves of biomass from this resource assessment can be evaluated by means of BioTrans (De Wit et al., 2010; Lensink and Londo, 2010) and PEEP (Berndes et al., 2010) the two models used in the REFUEL project to model the supply and cost of production of Biofuels and Bioenergy respectively.

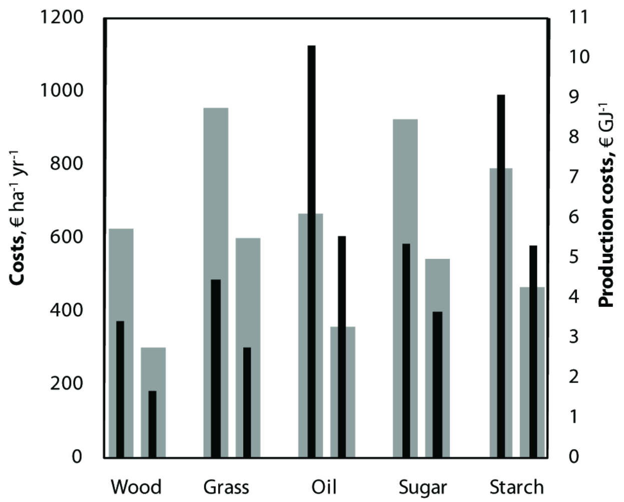
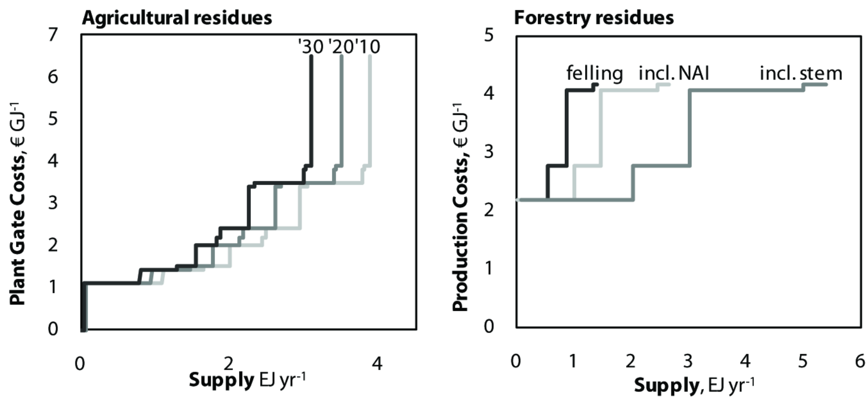


Figure 2-5 Production cost for 5 feedstock groups on area (grey bar, left axis) and energy basis (black bar, right axis). The left bars within a feedstock group refer to the WEC and the right bars to the CEEC.

2.4.2 Agricultural and forestry residue potential

Cost-supply curves are constructed for forestry and agricultural residues. The cost-supply curve for forestry information is compiled based on literature data. The supply potential of agricultural residues is derived from production figures on food and feed. Costs associated with production are derived from an overview of market prices in Europe.



NB - The cost level for Finland, 2.75 € GJ^{-1}, is applied to Sweden and Norway. The cost level of Poland, 2.18 € GJ^{-1}, is applied to Latvia, Lithuania, Czech Republic, Hungary, Slovakia, Slovenia, Estonia, Ukraine, Romania, and Bulgaria. The cost level of the Netherlands, 4.17 € GJ^{-1}, is applied to Belgium, Denmark, Ireland and Switzerland. The cost level of France, 4.07 € GJ^{-1}, is applied to Austria, Germany, UK, Portugal, Spain, Italy and Greece.

Figure 2-6 Cost-supply curves for agricultural and forestry residues.

The total supply potential for the agricultural residues decrease over time from 3.9 to 3.1 EJ y^{-1} between 2010 and 2030. This decrease can be explained from the residue to crop (RPR) ratio which decreases over time due to assumed yield increases. Cost levels range from 1.0 to 6.5 € GJ^{-1}. The total potential for wood resources depend on the fractions that are considered. European felling residues can amount up to 1.4 EJ annually. In addition, the annual growth of the standing trees (net annual increment, NAI), minus fellings and residues, provide an additional supply of 1.3 EJ y^{-1}. The harvested whole trees, mainly used in the timber sector comprise the largest supply with 2.7 EJ annually. The cumulative total forest supply potential is 5.4 EJ y^{-1}.

2.4.3 Total European biomass resource potential

Figure 2-7 depicts the annual biomass resource potential per country. The uncertainty bars indicate the range between the lowest and the highest yielding crops. The overall potential, under the base case, ranges between 8.0 and 24.6 EJ y^{-1}.

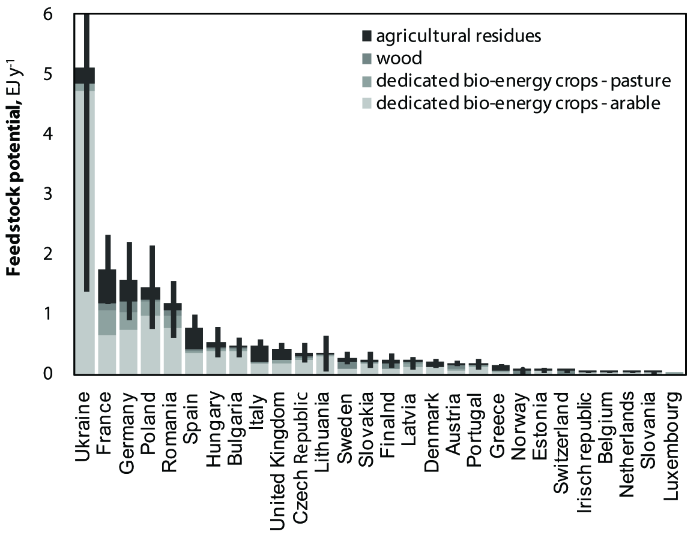


Figure 2-7 Country specific annual biomass feedstock supply potential by 2030.

2.4.4 Spatial bioenergy crop production potential and costs

Figure 2-8 (left) depicts the potential share of land that a region can allocate to bioenergy production by 2030, presented for five classes (a darker green shading reflects a higher share of land for bioenergy crops). The potential depends on i) the agricultural land available as a share of total land and ii) the share of that agricultural land which can be used for bioenergy production. The latter depends strongly on the productivity of food and feed production. In the scenarios it is assumed that the productivity of the food and feed production will increase, especially in the CEEC. As is clear from Figure 2-8 the majority of the feedstock supply is concentrated in the CEEC. The right graph depicts the spatial distribution of the production costs for woody crops for the year 2005. The spatial distribution of production costs in this figure is representative for the other crop groups assessed in this study. The spatial variation in production costs can mainly be attributed to variation in land (rental) prices and labour costs.

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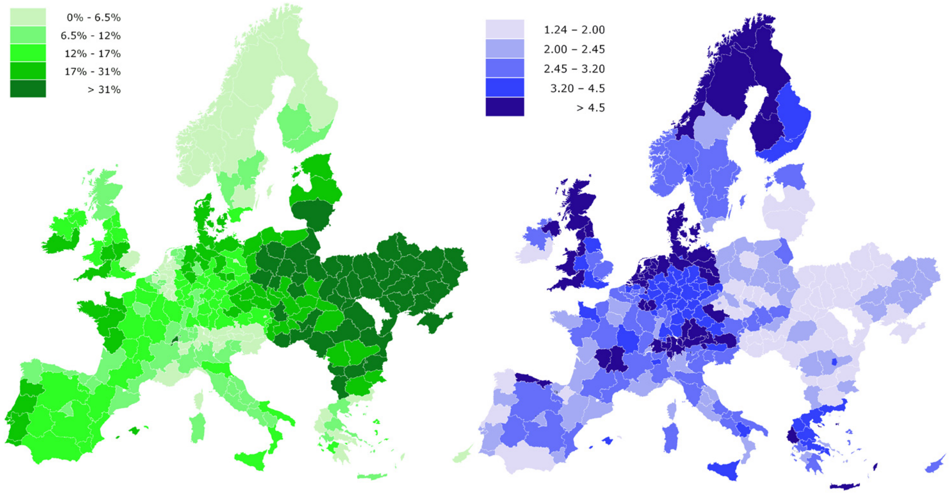

Figure 2-8 The 'surplus' land potentially available for the production of biomass by 2030 (left, green shades indicate the amount of surplus land as a percentage of the total land) and the production costs for woody crops in 2005 (right, blue shades indicate the production costs of woody crops in € GJ^{-1}) together indicate favourable locations for the production of biomass.

2.5 Discussion

The production of bioenergy crops connects to sustainability considerations in several ways, e.g. via the intensification of agriculture and associated land use change, the potential to reduce emissions compared to the fossil reference, etc.

The main driver to steer the freeing-up of arable land is intensification of the production of food crops. Application of an intensified management can, however, increase pressures on the environment and alter the (sustainable) use of resources. Some adverse effects that can result from intensified farming are soil degradation, loss of biodiversity *etc*.. Furthermore, increased use of resources can induce scarcity and depletion of resources. When adequately managed, however, such adverse effects can be minimized and prevented. An extensive farming practice (e.g. organic farming) on the other hand can reduce yields, and because of that require more land to produce equal amounts of food. Hence, there exists a trade-off between the farming intensity and the pressure on the environment on the one hand and the farming intensity and land requirements on the other hand.

The rate at which the intensification of agricultural production develops has considerable consequences for the available land for bioenergy production. While for the base case the available arable land can amount 660 000 km^2 this can be reduced by 20 000 km^2 under the low scenario or increased by 140 000 km^2 under the high scenario. For the extreme case that no intensification is assumed and hence that yield levels will not change compared to the current situation, available land will remain unchanged at a (2010) level which is about half of the potential projected for 2030.

One key assumption in this study, which has a profound impact on the projected biomass potential, is the presumed modernization of the agriculture sector in the CEEC driven by increased access to financial support facilitated by the recent accession of the CEEC to the EU. The extent to which funds actually induce modernization and restructuring is, however, unclear given the relatively recent date of the accession.

Dairy and animal production can be optimized with respect to the feed requirements (feed conversion efficiency) and land requirements. While progress on both aspects has been considerable, the increased implementation of landless production has freed up substantial areas of grassland in Europe. In principal these grasslands can be used for bioenergy crop production. Grasslands are, however, recognized for their (relatively) high level of agro-biodiversity. So, large-scale conversions of grassland to arable land would risk a reduction of biodiversity. Transition of (natural) grasslands can reduce biodiversity by several percents (Dornburg et al., 2008). Also connected to grassland conversion to arable land is the release of green house gas emissions upon tillage. The extent of the GHG emissions is much debated and depends on site, crop and management characteristics. When grasslands, making up about one fourth of the total agricultural land, are, however, excluded from bioenergy crop production, based on before mentioned sustainability considerations, then the available land for bioenergy crop production is seriously reduced.

One of the key drivers for the use of biomass for energy is the reduction of GHG emissions compared to their fossil reference. The ability to reduce emissions, however, varies considerably between different bioenergy crops and subsequent conversion routes. On average 1st generation biofuels have the potential to reduce GHG emissions by 0 to 45% while 2nd generation biofuels can reduce emissions by 70 to 90% (Londo et al., 2010).

2.6 Conclusions

The European biomass resources potential can vary largely, depending on a number of factors. Driven essentially by productivity increases in conventional food and feed production in CEEC and to a lesser extent in WEC; agricultural land can be freed up for the production of dedicated bioenergy crop production. For the scenario's considered, 'surplus' agricultural land can, between 2010 and 2030, amount 360 000 to 660 000 km^2 arable land, grassland and pastures can add an additional 50 000 to 240 000 km^2. Depending on the type of bioenergy crop cultivation and the land considered for production the primary energy content of the raw feedstock can amount between 1.7 and 12.2 EJ y^{-1} (variation between low and high scenario = 1.6 – 14.1) on arable land. The production of (herbaceous) lignocellulose crops considered for production on pasture land can contribute an additional 1.6 to 3.6 EJ y^{-1} (1.5 – 4.3). Additionally, substantial residual streams from established agricultural and forestry production can potentially be made available for bioenergy crop production. Agricultural residues from food and feed production can amount 3.1 to 3.9 EJ y^{-1}. Supply from forestry, both residues and stem wood, can amount 1.4 to 5.4 EJ y^{-1}. The maximum summed up total for all resources can amount 27.7 EJ y^{-1} by 2030.

The production costs at which biomass resources are available in Europe are variable, with significantly lower costs in CEEC than WEC. Main explanatory factors are lower land rent costs and labour costs for the CEEC. The greater part of the first generation feedstock supply is available at production costs of 5.0 to 15.0 € GJ^{-1} compared to between 1.5 and 4.5 € GJ^{-1} for second generation feedstocks. Cost differences can be attributed to the relatively extensive production practices and high yields for second generation feedstocks. The majority of agricultural residues can be made available to costs between 1.0 and 4.0 € GJ^{-1}. Forestry residue supply costs lay between 2.0 and 4.0 € GJ^{-1}.

Preconditions to develop the high production potential is that the agricultural practice in the CEEC is modernized, that lignocellulose crops for 2nd generation biofuels are commercialized and implemented on a larger scale and that significant residue streams are allocated to energy purposes.

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3 Productivity developments in European agriculture: Relations to and opportunities for biomass production

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ABSTRACT This chapter discusses if, how fast and to what maximum yield improvements can be realized in Europe in the coming decades and what the opportunities and relations are to biomass production. Historic developments in European crop and animal protein productivity between 1961 and 2007 show an mean annual growth rate of 1.6%. In relative terms developments are slower on average in the Netherlands and France at 1.0% y^{-1} than in Poland and Ukraine (USSR) at 2.2% y^{-1}. In absolute figures, however, growth has been considerable in WEC and modest in the CEEC. Yield trends further show that significant yield changes can be realized over a short period of time. Positive growth rates of 3 to 5% y^{-1} were reached in several countries and for several crops in several decades. In Eastern European countries during their transition in the 1990s negative growth rates as low as -7% y^{-1} occurred. Outcomes suggest that productivity levels can be actively steered rather than being just the result of autonomous developments. Current yield gaps differ greatly between Western Europe (France <10%) and Central and Eastern Europe (Poland and Ukraine 50-60%. This suggests that yields in Central and Eastern Europe, with dedicated agricultural policy, may be able to catch-up with Western European levels. Ideally, such a dedicated policy follows a leap-frog approach, meaning that past experience form the starting point for future policy development. Western European countries have developed in the direction of maximum attainable levels. This is confirmed by stabilizing yield growth rates over the last two decades. Yield improvements in this region may come from breakthrough innovations. Projections for regional growth rates differ significantly in literature resulting in different outlooks for biomass production. At the extremes the European bioenergy potential, assuming average bioenergy crop yields, can amount to 5.1–9.3 EJ y^{-1}. High yielding lignocellulose crops could double this potential. It is concluded that the potential to free-up agricultural lands for the production of bioenergy crops in Europe is considerable. The degree to and the pace at which yields develop will determine how much of the potential is opened up. Agricultural policy and technological development are key to open up the potential.

3.1 Introduction

The use of biomass resources for energy, chemicals and materials is expanding, globally and in Europe. Reasons for its use are resource diversification, emission mitigation, opportunities for rural development, *etc.*. The availability of sufficient and affordable biomass feedstocks is crucial for biomass to deliver a sizeable contribution as a resource for energy and materials production. Assessments are conducted to evaluate the availability and production costs of biomass resources at current and how these can develop into the future. Agricultural yield is an important factor that determines the land requirements to satisfy food demand and thus the quantity of land that can be freed-up to be used for dedicated biomass production for energy and materials. This study will look at past agricultural productivity and examine how it may develop in the future with the aim to assess the speed at which and the extent to which biomass resources can be produced in Europe.

Over the past decades, agricultural production has increased in Europe as a result of area expansion and increasing productivity. For example Western European yields have roughly doubled in five decades (FAOSTAT, 2009). Factors driving the demand for food and the agricultural production have been population growth and a changing diet towards a higher caloric intake. The key driving force for increasing agricultural productivities has been the intensification of agriculture, by mechanization and up-scaling, steered by dedicated agricultural policies. Ongoing production expansion in combination with a stabilizing European population (EUROSTAT, 2010) and caloric intakes create opportunities to allocate agricultural land to uses other than food production, one of which is bioenergy.

The potential to allocate land to bio-energy production has been assessed globally (Hoogwijk et al., 2005; Obersteiner et al., 2006; Smeets et al., 2007; Dornburg et al., 2010) and specifically for world regions, like Europe (de Wit and Faaij, ; EEA, 2006; Ericsson et al., 2006; European Commission (DG AGRI & DG EAE), 2006; Thrän et al., 2006; van Dam et al., 2007). Generally, these studies consider two developments: changes in the surplus land that is available for non-food production and changes in (bio-energy) crop yields (Smeets et al., 2007; Fischer et al., 2010). The combined results give the (technical) biomass production potential. Scenarios are used in order to account for uncertainties in the developments that are modeled and to make the impacts of these uncertainties on the biomass production potential explicit (Ewert et al., 2005; Rounsevell et al., 2005; Fischer et al., 2010). The potential studies use different assumptions and projections for future developments in crop yields and in livestock production. The possibilities to increase agricultural productivities, the rate at which this can be established and how this can be done are currently topics of debate. Therefore, the key discussion points in this paper are, to assess:
(i) if yields can improve further in the next decades,
(ii) at what growth rates developments can advance and
(iii) what maximum (sustainable) yield levels can be achieved.

To make explicit what the impact of developments in agriculture is on the European bioenergy production potential the used methodology is presented together with the paper's structure. Section 3 provides an overview of driving forces that have steered agricultural developments in Europe over the last five decades. Section 4 will illustrate quantitative developments in agriculture by presenting time-series for key inputs (labor, machinery, fertilizer and pesticide) and yields (wheat, rape seed, sugar beet and cattle) between 1961 and 2007 for two Western European countries (the Netherlands and France) and two Central and Eastern European countries (Poland and Ukraine). This is followed in section 5 by an overview of the trends in overall input application and yields for the four countries. In the same graph the key developments in policy, economy and the rural situation are presented below the quantitative trends. From this, temporal shifts within countries and differences between countries are identified and explained and future productivity development trajectories are hypothesized. Finally, in section 6 conclusions are drawn, suggestions for further research are made and recommendations are set out.

3.2 Methodology

3.2.1 Historic developments

The analysis starts (section 3 and 4) with an overview of historic developments and describes the fundamental driving forces that have shaped European agriculture over the last five decades. Historic developments describe the general economic situation, technological developments, agricultural policies and structural reforms. Furthermore, the historic overview illustrates how driving forces relate to each other, for example how agricultural policy has changed as an effect of the changing economic situation and the increasing impact of agriculture on the environment. First, the discussion is differentiated between developments in the Western European Countries (WEC) and the Central and Eastern European Countries (CEEC). The reason for this separate discussion is the distinctly different developments in these two regions at least until the 1990s due to different political systems. Secondly, more specific developments are illustrated in four countries France, Poland, the Netherlands and Ukraine. Given the distinctly different developments in the WEC compared to the CEEC, countries were considered from both regions. France is included because it is the largest producer in the WEC. Furthermore, France has historically played a key role in framing the European Union's common agricultural policy (CAP). The Netherlands has one of Europe's most efficient and technologically advanced agricultural sectors. Ukraine has been, due to its large land resources and good soil quality, one of the largest producers (and exporters) of agricultural products. Furthermore, its proximity makes it an obvious trading partner for the EU. Poland is the largest of the ten member states that joined the EU in 2004 and has a large agricultural sector. This selection does not consider any of the Mediterranean and Nordic countries.

Three dimensions were discerned that reflect the broader objectives of the agricultural policy: *supply and price stability, rural development* and *environmental quality*. The first two dimensions are derived directly from pillar I (direct agricultural payments) and pillar II (rural development) of EU's common agricultural policy (CAP) (AGRI). Environmental quality has become a more explicit part of agricultural policy over the years. In the synthesis section a diagram presents the evolution of inputs and outputs and the key factors that have shaped developments in productivity under the three policy dimensions over time.

To assess developments in agricultural inputs and outputs over time, time-series are presented. Comprehensive time-series data are available, mainly from the UN Food and Agricultural Organization statistics division (FAOSTAT) (FAOSTAT, 2009). Most data is recorded for the period 1961-2007. The focus of this study is on productivity developments in conventional agriculture, more specifically, on developments of land-bound agriculture. Four outputs are selected to represent improvements in productivity developments in European agriculture: wheat, rapeseed, sugar beet and cattle production. The three crops are widely produced staple crops in Europe and in the countries assessed in this study. Furthermore, each represents one of the main crop groups of starches, sugars and oil crops.

Cattle production represents developments in the production of livestock. Although livestock production itself, in the case of landless production, is not very land intensive, feed production is. The improvements in the production of livestock however focus on the efficiency to which feed is converted to meat (or dairy products). The indirect effects that (large-scale) feed imports may have on land use outside Europe are not further specified here.

The yield data give an overview of developments over time for the four countries relative to each other. The yield levels attained can also be compared to the maximum attainable yield that can be reached under local agro-ecological circumstances. The agro-ecological circumstances consider the soil and climate characteristics, usually under rain-fed conditions. The difference between the actual yield and the potential attainable yield is referred to as the yield gap. Opportunities to bridge the yield gap can come from changes in the agricultural management, land reform, *etc.*.

3.2.2 Data input

An overview of historic yield growth rates is presented to give insight into the development speed and direction, between regions, over time and between crops. Linear regression was performed on the 1961-2007 time series. Yield growth rates are presented per country, per decade, per crop and for the entire period. Furthermore, a yield growth rate distribution histogram is presented.

As a proxy for developments in input use, time-series are presented for four key inputs: machinery, labour, synthetic fertilization and pesticide use. The time-series describe the aggregated input per country divided by the total agricultural land cultivated in a year. A more elaborate explanation of data used and the modifications made to the data is presented in a footnote to Figure 3-2. The selected inputs have particularly facilitated modernization in agriculture, for example by mechanization, fertilization and weed and pest control. The selection however ignores other inputs such as water use (irrigation) and organic fertilizer (manure) application. Furthermore, it ignores production characteristics that have an effect on input use (efficiency) such as rotation schemes and farm size. The latter characteristics of agriculture are discussed in the country overview to explain developments in their broader context.

3.2.3 Synthesis

The synthesis section brings together the developments overview (section 3) and the quantitative trends (section 4) and derives and discusses cause-and-effect relations. Furthermore, the time-series data for the individual inputs and the individual outputs are combined on a country level to obtain aggregated trends for inputs and for outputs per country. For example, for all inputs (labour, machinery, fertilizer and pesticide) the trend in physical units is calculated as an index (base year 1961). From these four indexes an (un-weighted) average value is calculated for every year. The same routine is repeated for the outputs. The trends for aggregated inputs and aggregated outputs are presented in one figure. This provides a comprehensive overview of how, over time, aggregated inputs and outputs have developed, also relative to each other. Furthermore, in the same figure, below the quantitative input and output trends, the key developments in policy, economy and structural changes are presented for the three policy dimensions *price and supply stability, rural development* and *environmental quality*. This offers a visual overview of developments in input and output developments and the key driving forces that have steered these developments.

Next, the general trends that are observed for the WEC, the CEEC and Europe are evaluated. Historic developments are discussed in connection to the main driving forces that have facilitated growth and that have steered the direction and speed of developments. Building on these insights an outlook is sketched for how yields may develop into future. Part of this discussion is an overview of literature studies that have assessed and projected yield improvements for Europe in the coming decades. The key assumptions in the various studies, on which the projections are based, are presented and discussed. Based on both the detailed analysis of historic drivers and the literature overview, several development trajectories are illustrated for the WEC and the CEEC. These development pathways describe what preconditions in terms of policy and economic developments are required to reach certain yield growth rates over longer periods of time. Finally, the European agricultural lands that can be freed up in the future under the different yield development projections, assumed in the different studies, are presented. Assuming average bioenergy crop yields the raw biomass potential is calculated.

3.3 Historic developments in European agriculture

This section provides a chronologic overview of developments in the European agricultural sector over the last five decades. Structural changes and policy developments are described for the Western European Countries (WEC) for the Central and Eastern European Countries (CEEC) and more specifically for France, Poland, the Netherlands and Ukraine.

3.3.1 European agricultural policy and structural changes

Western European Countries. After the war years, European countries were determined to increase their productivity and rebuild their infrastructure. To achieve this goal countries designed national plans – like the French Monnet plan and the Dutch six year plan (A. Van den Brink, 1990). By the early 1950s, restoration in most countries had advanced, in isolation, to a point that allowed countries to broaden their scope with respect to strengthening their position through cooperation. A first step was the foundation of the European Coal and Steel Community in 1951 (ECSC, Treaty of Paris) which aimed to pool resources between member countries of the ECSC. Furthermore, it underlined the interdependencies between countries. The explicit framing of policy for agriculture was introduced with the foundation of the European Economic Community in 1957 (EEC, Treaty of Rome) under the Common Agricultural Policy (CAP). The CAP recognized natural, structural and social disparities between agricultural regions and aimed to (1) increase productivity, (2) ensure a fair living standard for the agricultural community, (3) stabilize markets, (4) secure supplies and (5) provide food at reasonable prices ((ed.), 1998). Two policy instruments were implemented to achieve these objectives: (1) Intervention prices provided a (supply) price guarantee regardless of (global) market prices; similarly (2) levies on imports and export refunds protected the internal market against low global market prices. The CAP objectives were met in the sense that agricultural production was increased and prices in the internal market were stabilized. The objectives were essentially overshot because decades later they resulted in food surpluses, adverse effects on the environment and trade distortions with the world market. As a result, opposition against the CAP increased both from within and outside the EU. Outside the EU the major opposition was directed at the distorting effects on global trade with non-subsidized producers. Within the EU criticism focused on the disproportionate benefit to larger farms while it failed to reduce the economic vulnerability of smaller farmers. Ongoing opposition led to the McSharry reform (1992) with its most important change being a shift in focus from pillar I (agricultural support) to pillar II (rural development support). The evolutionary process of decoupling eventually culminated in the 2003 CAP reform. Under the reform price guarantees were substituted by direct hectare-bound payments to farmers, the Single Farm Payments. To be eligible for support, farmers need to comply with standards concerning public, animal and plant health, environmental standards and keep their land in good agricultural and environmental condition (cross-compliance) (European Commission, 2009). The reform aimed to (1) control expenditures (2) deal with support budget expansion due to the accession of ten new member states, (3) provide a good starting point for multilateral agricultural negotiations and (4) address consumer and agricultural issues in agricultural policy ((ed.), 1998).

Central and Eastern European Countries. Agricultural policy in Central and Eastern European countries has until the late 1980s been influenced by socialist governed regimes. A high priority on adequate and affordable food supply led to substantial investments in inputs for agriculture. As a result, until the 1980s, farms were collectivised and closer cooperation between agriculture, distribution and food processing was stimulated. The effect of these measures on production and productivity gains was, however, less than expected. One reason for this was the high dependency of the rural population on agriculture. In the process of centralisation of resource (e.g. fertilizer) distribution there was increasing discrimination towards private farms. Although less than expected, production increased steadily, e.g. by farm specialisation, which in some countries even led to net exports of agricultural products. Subsequently, due to the desire to boost animal production, large but irregular imports of grains were required. In order to avoid over-dependance on imports, additional efficiency improvements were required.

These were achieved through the establishment of large agro-complexes, which further integrated production, distribution and processing. Ongoing inefficiencies in agriculture and in the economy in general could not live up to expectations which eventually led to reforms in the late 1980s and early 1990s (Turnock, 1996).

3.3.2 Country profiles: policy developments and structural changes

The Netherlands

Postwar rebuilding. In the post-war period efforts were directed at restoring and increasing agricultural productivity and decreasing costs and consumer prices. Over the course of five decades the role of primary agriculture (excluding secondary sectors such as manufacturing and processing) in the Dutch society and the contribution to the GDP declined gradually, from 10% in the 1950s to 2% currently. The total workforce in the agricultural sector was reduced by half. Total production in the agricultural sector (including horticulture) increased by as much as a factor of four and average food crop productivity more than doubled (Bruchem et al., 2008).

Intensification and up-scaling. In the beginning of the 1950s, the focus shifted to structural changes in the agricultural sector, laid down in the six-year-plan (Bruchem et al., 2008). To enhance productivity several changes were deemed necessary: intensification of the agricultural practice, Growth in the size of agricultural holdings and increasing farmer specialization. The Increased size of landholdings necessitated a widespread re-allotment campaign, which proceeded well into the 1980s.

Expansion and modernization. The 1960s and 1970s were characterized by economic growth, real GDP per capita increased by 4.9% per annum in the period 1963-73. This was accompanied by a sharp increase of capital input into the agricultural sector, facilitating rapid expansion and modernization (Van den Brink, 1990). This process was further spurred by a favourable fiscal regime which stimulated investments.

Quotas and fallow regulations. In the beginning of the 1980s this stimulating fiscal regime was largely abolished: combined with (record) high interest rates, investments stalled. Also the agricultural markets (nationally, in Europe and globally) were becoming saturated – a result of effective policy to increase productivity – which led to a change in policy. Support to farmers was reduced, production control mechanisms (e.g. quotation of grains, meat and dairy production) implemented and a fallow (set-aside) policy introduced.

Environmental legislation. The adverse effects to the environment as a result of ongoing intensification became increasingly apparent, leading, towards the end of the 1980s, to legislation that restricted organic fertilizer application (Centraal Planbureau (CPB), 2000). Together the new policies for quotas and set-asides combined with the economic situation and new environmental legislation caused an absolute reduction of inputs (minerals, energy, pesticides and fertilizers) and led to relative efficiency improvements in agricultural production. Further regulations on fertilizer use at the end of the 1990s led to sharp decreases as well as a reduction of nitrogen in fodder and an increase in feed-conversion efficiency (H. Zeijts et al., 2007). Although input levels were drastically reduced in absolute terms, the increase in productivity was only slowed slightly, indicating ongoing efficiency improvement. In the beginning of 2000, after two decades of steady decline, the use of pesticides increased again.

Decoupling productivity support. Moreover, for the first time in five decades, productivity levels stabilized and even decreased slightly. Several factors can be thought to be (at least partly) responsible for this; the set-aside policy which became obligatory (in 1992), stricter environmental and the decoupling of support from the productivity under the CAP.

France

Post-war rebuilding. The expansion of agricultural production after the Second World War has been particularly rapid in France compared to neighboring countries. This expansion is mainly due to the severe depression in the 1930s and 1940s when efficiency and innovation stalled due to low prices paid for agricultural produce and an abundance of work force. The 'First Plan' put a high priority on mechanization and fertilization. Fertilizer use quadrupled in the beginning of the 1960s compared to pre-war levels. The increased capital intensity in agriculture is clear from the expenses on input purchases which increased by 7.4% per annum in the period 1959-73 (Bergmann, 1983).

Up-scaling and modernization. The 1960s and 1970s were aimed at increasing production by stimulating up-scaling and modernization. Much of the policy aimed at realizing structural changes was implemented on the European level, while the French domestic policy was aimed at providing social assistance to poorer farmers during the transition. In the 1960s policy initiatives lay the foundation for modernization of agriculture. Policies included the creation of pension funds stimulating early retirement, measures to encourage farmer cooperation and the creation of local government institutions that facilitated farm up-scaling. To facilitate up-scaling and rearranging of farm land dedicated rural institutions (SAFER) purchased land on the market and sold it to good qualified farmers in larger plots. The up-scaling resulted in a decrease of farm numbers from 2.3 million in 1955 to 650 000 in 2005 while increasing the average farm size from 14 to 42 hectares over the same period (Corade et al., 2005). In addition, mortality of an aging farmer population and a reduction of farms that were succeeded by farmers' children spurred the transition to farm enlargement (Hough, 1982). As a result, the French rural areas depopulated, which weakened the socio-economic situation of the rural population and locally reduced the quality of the agricultural land (Jacques, 1992).

Productivity increases and crop portfolio changes. Two developments have increased the output of the French agricultural sector: an increase in average crop productivity and a gradual shift to more productive crops, e.g. from oats to wheat and maize (Hough, 1982). Combined, these developments have increased total output by 2.6% per annum between 1959-74 (Bergmann, 1983).

Environmental legislation. Gradually increasing fertilization has increased pressure on the environment. Surface water contamination with agricultural nutrients in particular has raised costs for water treatment and has put stress on biodiversity. Under the CAP the cross-compliance standards amongst others regulate that in order to be eligible for support, farmers must comply with strict environmental criteria, e.g. the nitrate directive (OECD, 2008). The French *national rural development plan* which started in 2000 aimed at establishing more sustainable farming systems by promoting e.g. extensive farm management, arable to pasture conversion *etc.* A vital part of the plan was to provide financial support to farmers who switched to organic farming. As a result there was a fivefold increase of land under organic farming between 1996 and 2003 (Häring et al., 2004).

Poland

State control on inputs. Contrary to the large-scale collectivization of agricultural land in most Central and Eastern European Countries (CEEC) after the Second World War, more than three quarters of Polish farmland has always been privately owned (Giovarelli and Bledsoe, 2001). State authorities, however, did not allow farmers to purchase their own agricultural machinery. Instead, state organized machinery purchases were mostly assigned to state-owned farms and to machinery stations that served co-operative farms. For this reason, animal power still dominated on 70% of private farms by 1970 (Pawlak, 2002). In addition, the production and distribution of fertilizers was centrally planned and subsidized by the state. Consequently, state owned farms, representing less than a fifth of the farmland consumed almost a third of fertilizers (FAO, 2003).

Reform: economic downturn sharp decrease of inputs. Initially, the application of fertilizers dropped sharply due to fertilizer subsidy abolishment and a weak overall economic situation (FAO, 2003). Reform in most Central and Eastern European Countries (CEEC) was aimed at the restitution of the formerly collectivised farm land. Although in Poland the majority of land was privately owned, the country had to privatise its large state farms, making up 20% of total farm land. Under the centrally planned government, labour efficiency was low, especially in agriculture. Market liberalization during transition induced a strong reduction of demand for agricultural labour, thereby causing an outflow of labour from agriculture. This effect was most profound in regions that were dominated by state-owned farms. However, the much needed reallocation of labour between sectors, mainly from agriculture to industry and services, was severely hampered by the low level of education of agricultural workers (Dries and Swinnen, 2002). At the same time, farmers initiated off-farm activities to improve their income levels (Fałkowski et al.).

Accession to the EU. The accession of Poland to the EU has significantly increased the total support budget for agriculture. Total expenses for agriculture support almost tripled from 1.3 billion euro in 2003 (the year before accession) to 3.7 billion euro in 2005. About half of this increase comes on the account of EU funds (CAP and structural funds) and half on increases of the Polish national budget on agriculture (Poland, 2006). As a result real agricultural income per worker more than doubled (107%) between 2000-09 (Eurostat, 2010).

Ukraine

Post-war rebuilding. Postwar Ukraine was aimed at restoration of its infrastructure and industry. Agriculture was organised in kolkhoz (cooperative farms) and sovkhoz (state farms). While state farm workers were paid a salary, cooperative farm workers were paid in money and in kind depending on the realised harvest. This system of variable payment according to harvest combined with a year of crop failure due to severe drought caused a famine in 1946-47, immediately after which agriculture was largely collectivised (Åslund, 2009; Ministry of Foreign Affairs of Ukraine, 2009).

Collective farming. In the decades that followed agriculture was characterized by centrally planned collective farming. The modest growth in agricultural productivity between 1950 and 1980 in the USSR can be ascribed to three main factors. Population growth was low and even negative in some regions; hence food demand did not increase. Labour efficiency increased, mainly due to increased mechanization. Farmers used this progress to expand the area they cultivated rather then to use their land more efficiently. Consequently, this increased the total production, but not the productivity per unit of land., iii) Lastly, state ownership gave little incentive for farmers or managers to maximize output of the land (Wong and Ruttan, 1986).

Increased meat production. Around 1970 the Soviet Union observed the disparity between animal protein consumption between the Soviet Union and the US and Western Europe and wanted to close this gap. As a result of this, the Soviet Union placed a high priority on the increase of meat production. This policy placed a high demand on grains for animal feed up to the point where domestic production was deemed insufficient. This led to substantial, but irregular, grain imports from the world markets. The desire to keep consumer prices stable led to a situation where real yet implicit subsidies for agriculture were increasing. This policy was very successful in raising meat consumption: by 1990 USSR meat consumption equalled that of the UK while GDP per capita was only a third of that in the UK (Sedik, 1993; USDA (Osborne and Trueblood), 2003).

Reform: liberalization and subsidy elimination. After the dissolution of the Soviet Union in 1991, Ukraine became an independent state which set into motion nationwide political, economic and institutional reforms. Agricultural production plummeted after reforms were implemented. Livestock inventories in the entire Russian Federation (including Ukraine) fell sharply (United States Department of Agriculture (USDA), 2002). Cattle herds were reduced by more than half between 1988 and 2000. The drop in domestic grain production can be largely attributed to the reduction of grain used for feed which fell 66% (Sedik et al., 2003). Key drivers of these rapid changes included trade and price liberalization and land reforms. However, the elimination of subsidies for livestock producers caused a sharp decrease in farm income. In addition, the possibility to adapt to these new and open market circumstances was hampered because institutional reforms were only implemented much later. These policy measures were anticipated to induce a short term contraction, after which market mechanisms would recover productivity, by the realignment of price levels (Åslund, 2009).

2000s. State farms officially ceased existence by 2000. However, after a decade of reform in Russia (and other Soviet states) the forecasted increase of agricultural productivity and expansion of grain exports had yet to occur (Liefert et al., 2003). After a sharp decrease in fertilization levels during the 1990s, applications have recovered slightly, although they are still considerably lower than recommended. The modest use of inputs is not so much a matter of availability as a matter of limited financial means. For example, the high market prices paid for imported pesticides made Ukrainian farmers apply less costly and less effective domestic options. In addition, mechanical weed control is still widely used.

Modern harvesting equipment is also lacking. Because of this, harvesting takes longer, a high share is lost (10-20%) and the quality of the harvest is generally poor. Despite the lack of adequate resources, production and exports have increased in recent years due to favourable weather conditions and improved crop management on larger farms facilitating record yields (USDA, 2004).

3.4 Historic quantitative trends: yields and inputs

This section presents quantitative time series that – complementary to the storylines in the previous section – explain and put into context the observed productivity and input level developments. Data are obtained from two United Nations (UN) statistics bodies, the UN Food and Agricultural Organization's (FAO) statistics division FAOSTAT (FAOSTAT, 2009) and the UN International Labour Organization (ILO) (LABORSTA, 2009).

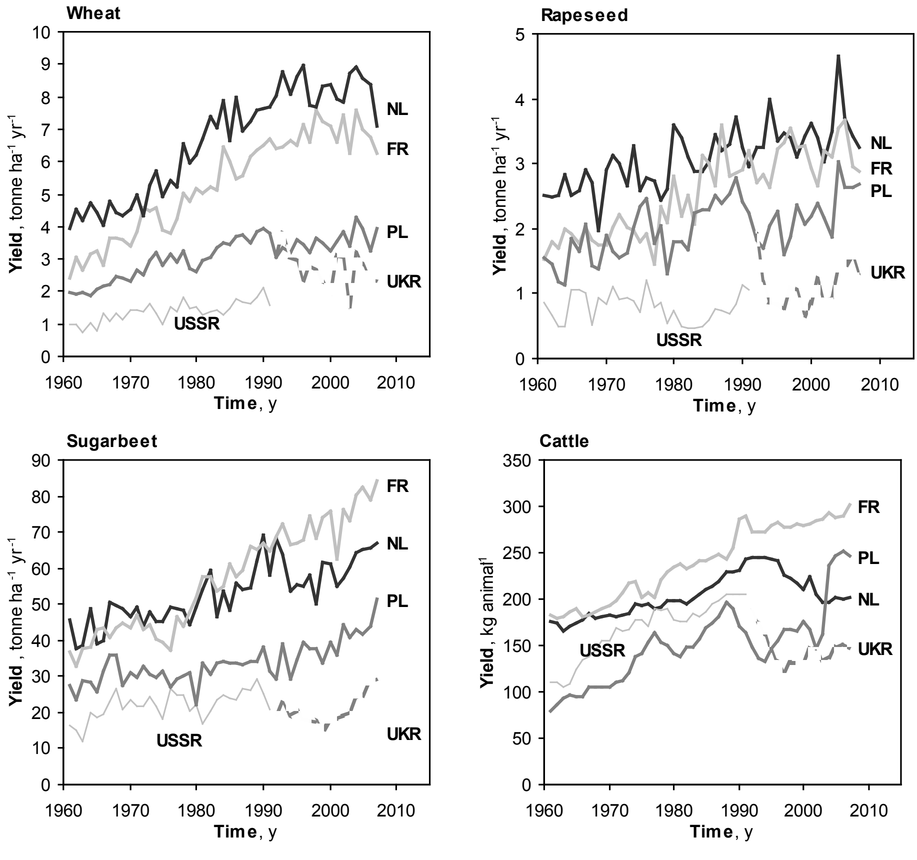


Figure 3-1 Historic yield developments (1961-2007) for the crops wheat, rapeseed and sugar beet and the production of cattle for the countries France (FR), the Netherlands (NL), Poland (PL), Ukraine (UKR) and the former Soviet Union (USSR). Data derived from FAOSTAT.

3.4.1 *Crop and animal meat productivity*

Depicted in Figure 3-1 are the historic developments (1961-2007) for three crops and cattle production for the countries France, the Netherlands, Poland and Ukraine (FAO, 2006). Also depicted are the developments in the former Soviet Union, since Ukraine was part of the Soviet Union prior to 1992.

Several observations follow from Figure 3-1. Generally, productivity developments show a continuous upward trend over 50 years (except for Ukraine). The Eastern European countries, Poland and Ukraine, had lower productivities than the Western European countries, France and the Netherlands. This is an indication that the yield gaps in Central and Eastern Europe are larger compared to Western Europe. Furthermore, at the time of the transition of the political (and financial support) system in Ukraine and Poland, Ukraine experiences clear decreases in all crops as well as cattle, whereas Poland's yields decreased less rapidly, stabilized, or even increased in the case of sugar beet.

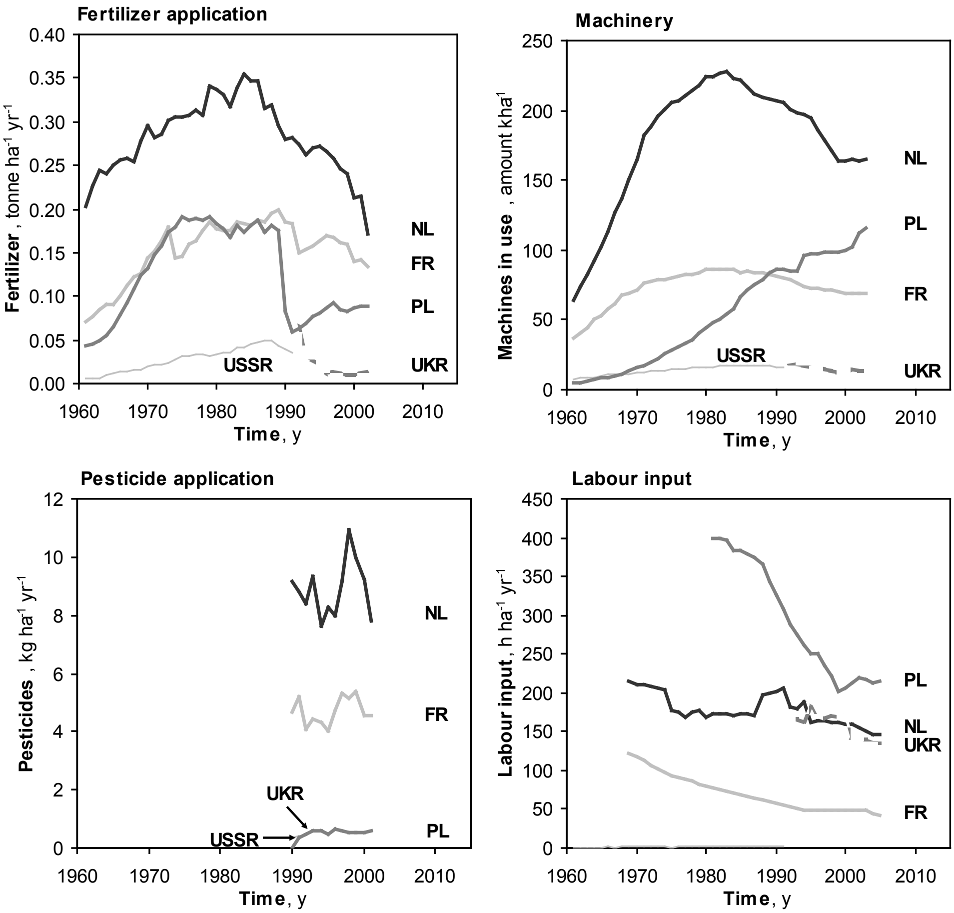
The Netherlands show a modest development of cattle productivity and negative growth in the 1990s and 2000s. This difference in productivity with France is explained from the large share of dairy cows that are not optimized for meat but mainly for milk production.

3.4.2 *Inputs: resource use in the agricultural system*

Agricultural production makes use of a multitude of production factors (inputs) with application levels differing per farm, region, crop *etc.*. As a proxy for development trends in input use national aggregate time-series are presented for four key inputs, machinery, labor, fertilization and pesticide use. Although this selection ignores many other inputs such as irrigation, farm size, *etc.*, it covers some important aspects – mechanization, nutrient application and weed and pest control – that have shaped agricultural development over the last decades.

Figure 3-2 shows a time series overview of four resources – fertilizer, machinery, pesticides and labour – used in the agricultural sector in the countries the Netherlands, France, Poland and Ukraine. Data are obtained from the UN FAOSTAT (FAOSTAT, 2009) and the UN LABORSTAT database (LABORSTA, 2009). The indicators are specified per unit of land (hectare) to make them comparable between countries and over time. To obtain an indicator per unit of land the aggregate consumption is divided by the amount of agricultural land that is cultivated per annum.

Labour and machinery (or capital) are substitutes for each other, although not one to one. This is roughly confirmed in Figure 3-2, where labour input generally decreases and machinery use increases over time. Based on the non-linear relation between labour and machinery, at least for the Netherlands, a faster decline in labour could be expected based on the rapid increase in machinery that was put into use. This also, to a lesser extent, may apply to France and Ukraine. In these countries this effect is not clearly visible, possibly because the additional machinery put to work did not (entirely) substitute labor that was previously done by hand, but rather it led to further intensification and higher productivity per unit of land.



Footnote to the figure

- Fertilizer application = Total Fertilizer+ *[FAOSTAT] / Agricultural area [FAOSTAT]*
- Machinery = (Harvesters-Threshers *[FAOSTAT]* + Tractors Agric. Total *[FAOSTAT])* / Arable land and permanent crops *[FAOSTAT*]
- Pesticide application = (Insecticides *[FAOSTAT]* + Herbicides *[FAOSTAT]* + Fungicides&Bactericides *[FAOSTAT]) /* Arable land and permanent crops *[FAOSTAT*]
- Labour input = Employment in the agricultural sector [LOBARSTAT] * 1400 *[working hours per year] / Agricultural area [FAOSTAT]*

Figure 3-2 Resource inputs in the agricultural sector for the resources labour, machinery, fertilizer and pesticides for the countries the Netherlands (NL), France (FR), Poland (PL) and Ukraine (UKR) and the former Soviet Union (USSR). Modified (see footnote) data, derived from FAOSTAT (FAOSTAT, 2009) and LABORSTAT (LABORSTA, 2009).

Contrary to the latter observation, although fitting in the trend of modest productivity increases, Poland seems to comply more with the substitution relation.The (rapid) decline in labor, however, should also be viewed in the light of the large inefficiency in the workforce during the socialist era. An additional observation is the peak in machinery use in France and the Netherlands around the beginning of the 1980s. This is due to an increase in the average machine power and the emphasis on environmental regulations which focused on environmental quality rather than on output. The differences in the absolute levels of labor per hectare, for example between the Netherlands and France, may be explained by the different crop and livestock patterns in each country's agricultural sector.

Fertilization levels have increased in all countries until the end of the 1980s, after which rates declined. Declining levels have different reasons for the CEEC compared to the WEC. In Eastern Europe the decline in fertilizer application levels in the early 1990s is rapid, caused by the collapse of socialist regimes and the abrupt abolishment of agricultural subsidies. In Western Europe, the gradual decline in application levels is the result of the implemented environmental legislation such as the nitrate directive.

Pesticide application statistics are available from 1990 until 2001 and are therefore more instructive with respect to the differences in absolute application levels than that they provide information on trend developments. For example, the Netherlands on average apply almost double the pesticide amounts compared to France.

3.4.3 Historic yield trends

Table 3-1 depicts the absolute and relative productivity developments for the three crops and cattle production for the four countries assessed for the period 1961-2007 and per decade. The numbers are obtained by performing linear regression to the data presented in Figure 3-1 for the periods indicated in Table 3-1.

Historic developments in European crop and animal protein productivity between 1961 and 2007 show an average mean annual growth rate of 1.6%. In relative terms developments are slower on average in the Netherlands and France at 1.0% y^{-1} than in Poland and Ukraine (USSR) at 2.2% y^{-1}. In absolute figures, however, growth has been considerable in WEC and modest in the CEEC. The volatility in average growth rates is higher in the CEEC than in the WEC.

The long term historic trends on a country level are measured by the relative growth rates for the period 1961-2007 (see Table 3-1). For all crops, France shows the highest long term growth rates (2.5%–3.6%). In the Netherlands wheat yields have increased significantly at 2.7% y^{-1}. Although, lower when measured in relative growth rates, in absolute terms the growth in wheat yields in the Netherlands (110 kg ha^{-1} y^{-1}) barely outperforms France (104 kg ha^{-1} y^{-1}. Consequently, the difference between relative and absolute growth rates is caused by the higher absolute yield in the Netherlands in the base year (1961). Relative growth rates for sugar beet and rape seed are in the same order for the Netherlands and Poland in relative terms. Measured in absolute numbers, the average annual growth in the Netherlands is substantially higher than in Poland for both crops. Developments in cattle production show a different picture. Poland has increased productivity rapidly in the 1960s to 1980s. During the 1970s cattle productivity increased at an average of 6.1% y^{-1}. France shows a modest and stable development in cattle productivity in the period 1961-2007 (1.6% y^{-1}). Cattle productivity in the Netherlands developed modestly with an acceleration in the 1980s but negative growth in the 1990s and 2000s.

Table 3-1 Absolute productivity increases and relative growth rates for the period 1961-2007 and per decade for the crops wheat, rapeseed, sugar beet and cattle production for France, the Netherlands, Poland and Ukraine.

		Yield development 1961-2007	**Annual increase** Period	per decade				
			1961-2007	1961-69	1970-79	1980-89	1990-99	2000-07
		kg ha^{-1} y^{-1} kg $an.^{-1}$ y^{-1} *(%)*	kg ha^{-1} y^{-2} / kg $an.^{-1}$ y^{-2} *(% y^{-1})*					
Wheat	France	2.4 – 6.3	104	136	96	125	99	-65
		(164)	*(3.6)*	*(5.2)*	*(2.5)*	*(2.5)*	*(1.6)*	*(-0.9)*
	Netherlands	3.8 – 7.1	110	31	170	95	37	-51
		(123)	*(2.7)*	*(0.7)*	*(3.8)*	*(1.4)*	*(0.5)*	*(-0.6)*
	Poland	2.0 – 3.9	39	67	59	116	-23	56
		(83)	*(1.8)*	*(3.6)*	*(2.3)*	*(4.1)*	*(-0.6)*	*(1.6)*
	Ukraine[a]	1.0 – 2.3	*n.a.*	44	14	47	-152	-6
		n.a.		*(5.1)*	*(1.0)*	*(3.6)*	*(-4.5)*	*(-0.2)*
Rapeseed	France	1.5 – 2.9	40	24	6	-8	60	36
		(113)	*(2.5)*	*(1.4)*	*(0.3)*	*(-0.3)*	*(2.1)*	*(1.2)*
	Netherlands	2.5 – 3.3	25	-16	-56	-2	20	7
		(46)	*(1.0)*	*(-0.6)*	*(-1.8)*	*(-0.1)*	*(0.6)*	*(0.2)*
	Poland	1.6 – 2.7	21	25	8	13	12	85
		(64)	*(1.4)*	*(1.7)*	*(0.4)*	*(-0.4)*	*(-0.6)*	*(4.0)*
	Ukraine[a]	0.9 – 1.3	*n.a.*	24	-26	-3	-105	85
		n.a.		*(3.5)*	*(-2.7)*	*(-0.4)*	*(-7.4)*	*(9.4)*
Sugar beet	France	37 – 84	1024	1249	82	1267	654	1967
		(140)	*(3.1)*	*(3.6)*	*(0.2)*	*(2.4)*	*(1.0)*	*(2.8)*
	Netherlands	45 – 67	489	1041	37	704	-1204	1430
		(54)	*(1.2)*	*(2.6)*	*(0.1)*	*(1.4)*	*(-1.9)*	*(2.5)*
	Poland	28 – 51	319	910	-150	742	334	1386
		(56)	*(1.2)*	*(3.5)*	*(-0.5)*	*(2.6)*	*(1.0)*	*(3.7)*
	Ukraine[a]	16 – 29	*n.a.*	1258	68	970	-683	1840
		n.a.		*(9.0)*	*(0.3)*	*(5.0)*	*(-3.2)*	*(11.3)*
Cattle	France	182 – 301	2.8	0.8	2.4	2.0	-0.3	2.6
		(75)	*(1.6)*	*(0.5)*	*(1.2)*	*(0.9)*	*(-0.1)*	*(0.9)*
	Netherlands	176 – 202	1.1	1.3	1.7	4.0	-2.3	-2.2
		(30)	*(0.6)*	(0.7)	*(0.9)*	*(2.1)*	*(-0.9)*	*(-1.0)*
	Poland	80 – 246	2.5	3.0	6.5	6.6	1.0	15.2
		(126)	*(2.7)*	(3.6)	*(6.1)*	*(4.9)*	*(0.6)*	*(10.1)*
	Ukraine[a]	110 – 146	*n.a.*	6.3	3.4	3.7	-8.6	1.6
		n.a.		(6.3)	*(2.1)*	*(2.1)*	*(-4.9)*	*(1.2)*

NB – The relative productivity increase shown for Ukraine for the decade '90-'99 is actually the increase in the period 1992-99. The numbers indicated for the decades '61-'69, '70-'79 and '80-'89 are based on trends for the former USSR of which Ukraine was part prior to 1992.
- Negative growth rates indicated in grey.
- *n.a.* = not applicable.

The breakdown of relative growth rates per decade allows for observation of trend discontinuities, accelerations and decelerations. After decades of growth in French wheat yields stabilization and even negative growth is visible in the period 2000-07. A similar trend can be seen for wheat yields in the Netherlands. For other crops in the Netherlands and France no such stabilization of yield growth figures in the last two decades can be seen. The most apparent trend discontinuities are the sharp negative growth rates for all crops and cattle in Ukraine in the period 1992-99, ranging from -3.2 (sugar beet) to -7.4% y^{-1} (rape seed). After this sharp negative growth, however, the productivity of rapeseed and sugar beet both showed sharp growth in the 2000s. A similar trend can be seen for Poland where growth stagnated and even contracted in the case of wheat and rape seed during the 1990s. However since 2000 Poland has experienced growth in yields that exceeds the country's historical averages.

Figure 3-3 shows a visual representation of Table 3-1 in the form of a frequency distribution histogram for the growth rates per decade (n = 80). From Figure 3-3 two observations stand out: Growth rates in the CEEC are more volatile than in the WEC and growth rates in the range of (-1)–0 % y^{-1} to 5–6% y^{-1} occur most (frequency ≥ 4).

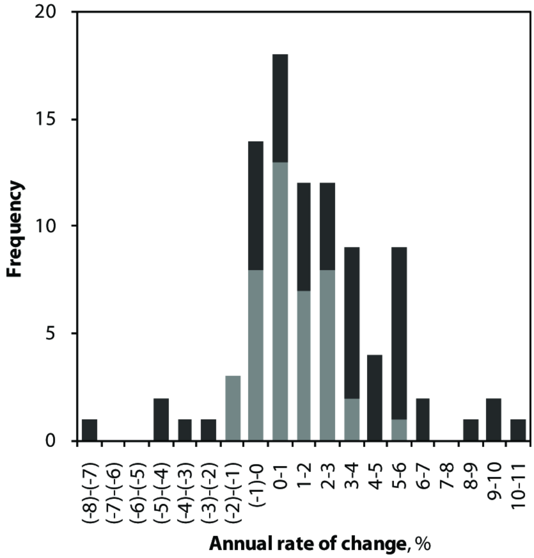


Figure 3-3 Frequency histogram of the annual growth rates (analyzed per decade) observed for the three crops and cattle production for four countries, here aggregated for the two regions of WEC (light) and the WEC (dark), between 1961 and 2007 (n = 80).

3.5 Synthesis

3.5.1 Country developments: trends and driving forces

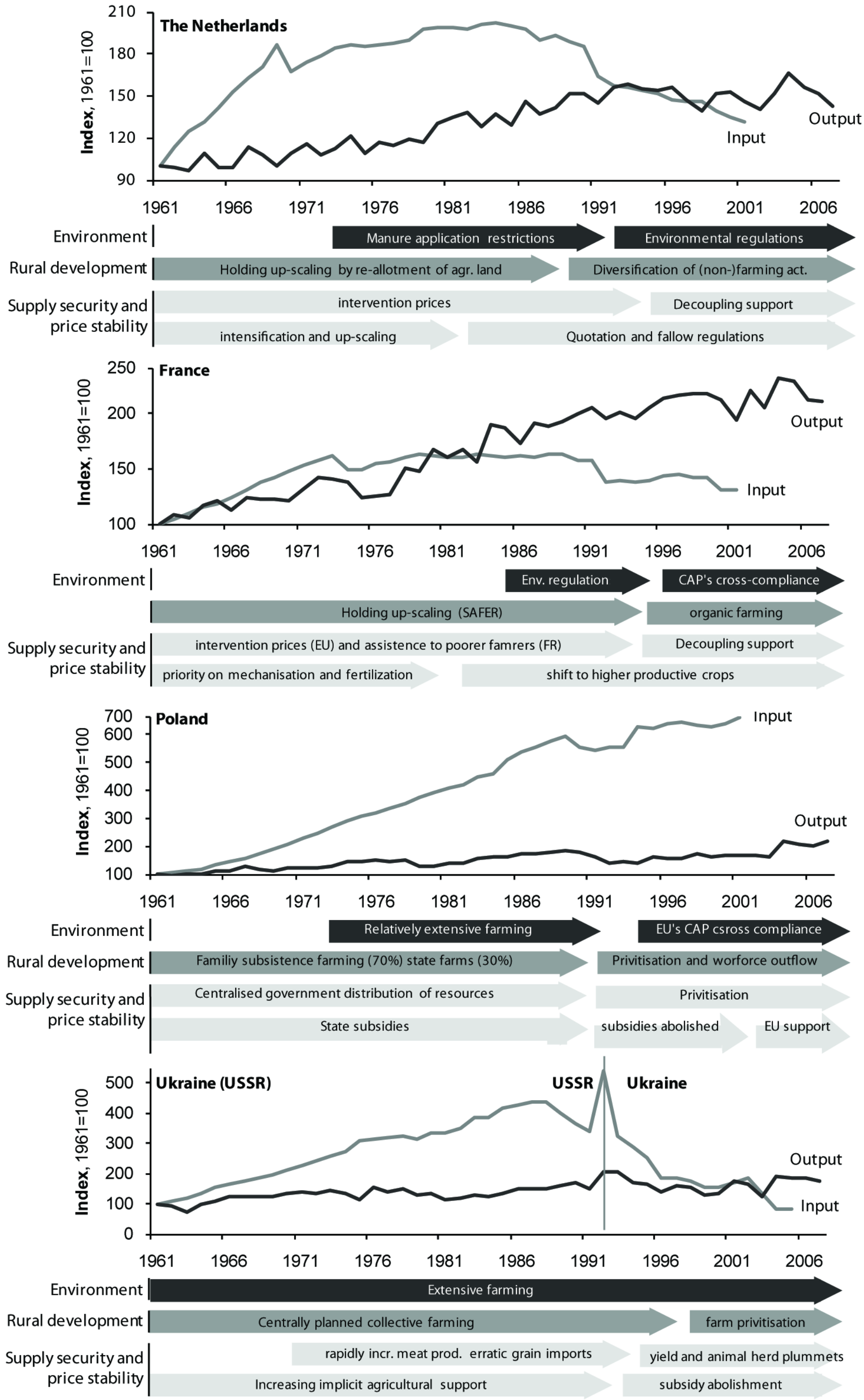
Figure 3-4 shows the aggregated developments for productivity and inputs over time together with the main driving forces, distinguished by the three policy dimensions of supply and price stability, rural development and environmental quality. The productivity and input aggregates are calculated as explained in section 2 based on the data shown in Figure 3-1 and Figure 3-2.

The Netherlands. The 1960s are characterized by rapid economic growth facilitating capital investments in agriculture. Figure 3-4 shows increasing aggregate inputs in this period, mainly on machinery and fertilizer. Mechanization raised machinery purchases (+220%) in the period 1961-75. This was partly at the expense of labour which decreased slightly. Fertilization levels increased significantly over the same period. Although aggregate productivity increased over this period, it did so much more slowly than aggregate inputs. However, those large-scale investments laid the foundation for future growth. A vital incentive was the intervention price guarantee, which provided a stable investment climate and formed a stimulus for maximizing output. Similarly, a re-allotment campaign increased the average farm size which led to scale advantages, farmer professionalization, and a migration of workers from agriculture to the industry and service sectors. Towards the end of the 1970s and the beginning of the 1980s, input levels stabilized. It became apparent that the EU's production-focused policy had been successful in providing a stable and adequate supply of food. At the same time, general concerns had risen about adverse effects of agriculture on the (local) environment, e.g. acidification and eutrophication. In the Netherlands, manure application to the fields was responsible for eutrophication, and application levels were restricted. Subsequently, the use of synthetic fertilizer peaked by the mid 1980s. Apart from a manure surplus, EU's dairy markets were saturated which led to a quota on milk production. As a result, towards the end of the 1980s, policy objectives shifted from output-maximization to a quality-focused approach. The first step was made in the beginning of the 1990s, but the ultimate decoupling of support schemes from production were implemented in the early 2000s. This also reduced the absolute support levels which offered possibilities for farmers to diversify to off-farm activities, hence increasing economic resilience.

Ukraine and the USSR. Agriculture in the USSR was organized around collective farms. Apart from the rural life this affected farm management and thereby input levels. For example, since farm labour was so abundant there was little need for farm mechanization. Significant growth was seen in fertilization levels, which increased ten-fold until the mid 1980s. The five-fold increase in aggregate input levels over this period can largely be ascribed to fertilizer use and machinery purchases. This considerable relative input growth is merely caused by the low levels in the beginning of the 1960s; in the 1980s the levels cannot be considered mature yet. Growth was stimulated by state investments, implicitly subsidizing the agricultural sector, and expansion of agricultural land cultivated (Zhang, 1997). Figure 3-4 shows a gradual but modest increase in USSR productivity levels until the late 1980s. The policy introduced in the 1970s to raise animal meat production was very successful in increasing total production and productivity levels. As a consequence, the USSR had to import large quantities to meet feed demand. The increasing aggregate inputs (technical change) did not fully materialize into augmented productivities. The main reason for this was a decline in efficiency (Trueblood and Coggins, 2003). Figure 4 shows a peak around the 1992 dissolution of the USSR when data for Ukraine were used instead of the USSR. From this moment a sharp decline is visible in input levels and productivity. Grain production fell 31% in the period 1990-95, after three decades of growth, due to productivity decline and a reduction of the land cultivated (Zhang, 1997). Reforms in the agricultural sector and economy wide were responsible for this decline. The abolishment of subsidies to agriculture sharply reduced farm income. The gradual process of privatization combined with a lack of adequate supportive policy hampered possibilities to adapt to the new circumstances. Productivity and input levels by the end of the 1990s had almost fallen back to levels of the 1960s. During the beginning of the 2000s after the fall in productivity and inputs, levels recovered somewhat, but were still below the levels of the early 1990s (The World Bank, 2008).

France. Agricultural productivity increased gradually in the 1960s and accelerated during the 1970s to mid 1980s. Induced by investments, input use (technical change) was stimulated. Initially input use did not fully materialize into productivity increases, explaining a decline in the input-output ratio (Figure 3-4) in the 1960s. From the 1970s onwards the technical change more than offset minor efficiency losses (Trueblood et al., 2003), thereby increasing the input-output ratio. Contrary to crop productivity developments, increases in livestock productivity were mainly steered by efficiency improvements (Jones and Arnade, 2003). Whereby technical change is steered mainly by mechanization and increased fertilizer use (Figure 3-2). After sharp input increases in the 1960s, input levels stabilized around the mid 1970s. Despite stabilizing input levels, productivities increased thereby increasing the input-output ratio. These further efficiency gains came from farm up-scaling, farmer professionalization and ongoing crop specialization. Average farm size increased from 14 to 42 hectares between 1955 and 2005. This had a major influence on rural life which was previously small-scale and family run. As a result, there was a transformation to farmer professionalization and an outflow of workforce towards services and industry. Furthermore a shift was made towards the production of high yielding crops, e.g. from oats to grains and maize. Since the late 1980s, input levels have decreased and productivity growth has decreases. The input decrease can be ascribed to decreasing fertilizer use and a reduction of machinery purchases. Adverse environmental effects due to (over) fertilization led to implementation of stricter environmental regulations which decreased the use of fertilizers. In addition, machinery input decreased because mechanization was by that time wide spread and farm equipment increased in average power. From the 1990s and proceeding into the 2000s, the decoupling of financial production support and an increase of land under organic farming, prolonged the gradual trend of decreasing input levels. This also led to a further decrease in productivity growth. The (new) agricultural policy put more emphasis on quality standards of the land to be eligible for financial support.

Poland. Poland's agriculture was largely centrally planned and strongly subsidized until the late 1980s. Although subsidy allowed for rapid and considerable increases of inputs, resource distribution was uneven between state and private farms. Large-scale machinery purchases supported rapid mechanization, although this occured mainly on state farms through the 1970s. Also fertilizer input increased rapidly. An uneven and distorted allocation of resources and a lack of economic incentive for efficient use of inputs, however, translated into modest productivity increases, reflected in a decreasing input-output ratio (Figure 3-4) (Anderson and Swinnen, 2008). Despite stabalising fertilizer levels around the mid 1970s and sharply decreasing labor inputs, aggregate inputs continued to increase mainly due to strong ongoing mechanization. Although mechanization increased the agricultural efficiency, on the input-output ratio the effect was neutralized because of poor resource distribution and modest farm up-scaling (Rungsuriyawiboon and Lissitsa, 2006). In the late 1980s, just before transition, subsidy levels peaked.



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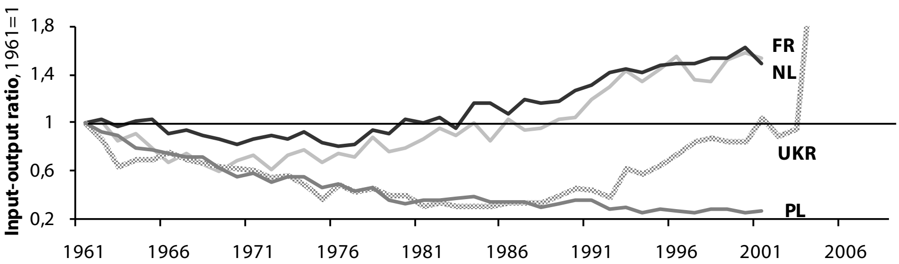

Figure 3-4 Aggregated developments in productivity and resource inputs for the Netherlands, France, Poland and Ukraine (previous page) and the input-output ratios for all countries for the period 1961-2007.

The transition in the beginning of the 1990s was characterized by subsidy cuts (or abolishment) for farmers and consumers, leading to decreasing farm income and soaring consumer prices. Cutting subsidies led to a 66% decrease in fertilizer consumption in just two years (1989-91). Fertilizer use fell to levels used in the 1960s while machinery purchases temporarily leveled off. Thus, for Poland, machinery is the most influential component of aggregate inputs because it has increased most rapidly in relative terms. As a result, the aggregated input development for Poland (Figure 3-4) only shows a slight fall in the beginning of the 1990s. Induced by falling input levels (Csaki, 2000) crop yield levels dropped, only to recover to 1980 levels by the mid 2000s. After the collapse due to subsidy abolishment in the course of the 1990s subsidies again increased substantially in order to restore farm income and consumer prices. These ad hoc subsidy schemes were later on replaced by a more comprehensive agricultural policy with an eye on Poland's accession to the EU. Upon accession farm income increased substantially because Poland came to fall under EU's CAP (Anderson et al., 2008), which translated into higher productivities and a stabilizing input-output ratio.

3.5.2 General trends and outlook

Historic yield developments reveal a larger volatility for the CEEC than for the WEC. The 1990s collapse of yields in the CEEC, caused by the transition from centrally planned to market economies stands out in this respect. Due to the discontinuity in the productivity development over time, a continuation of the historic trend into the future would suggest modest growth, thereby potentially underestimating the future land that could be freed-up by ongoing productivity increases. A cause-and-effect relationship can be derived by an evaluation of the economic and policy driving forces (cause) and their influence on productivity developments (effect). Apart from a larger volatility, FAO figures show that yield gaps are significantly larger for the CEEC than for the WEC. For wheat yields Poland and Ukraine realize only 40 to 50% of their agro-ecological potential compared to more than 90% in France (FAO, 2003). Preconditions to close this gap are for example, adoption of improved technologies and practices and an adequate transport infrastructure. Meeting these preconditions relies largely on economic development and supportive policies.

For the WEC similar discrepancies exist between an outlook that is based on a continuation of historic growth figures and an outlook based on the driving forces that shape agricultural productivity. Yields in the WEC have, on average, shown considerable growth for several decades. Continuation of this trend would therefore imply substantial growth for the (near) future. Inspection of the driving forces that have facilitated this growth may, however, suggest that the future growth potential is less than the realized growth in recent decades. Historic growth was established through structural reforms, modernization, economic progress and generous government support for agriculture. Together, these developments have facilitated a gradual increase of yields in the direction of maximum attainable levels. Closer scrutiny of historic trends furthermore shows a gradual decline in the annual growth, especially over the last two decades. In addition to the closing yield gap, at the beginning of the 1990s, the EU's CAP moved from an output oriented to a 'quality' focused support scheme. This also fits the ambition to steer away from the protection of the inner (European) market to open opportunities for competition with the world market. Also organic farming expanded in Western Europe over this period. An upward deviation from the historic trend may come from breakthrough innovations that have the potential to improve the production frontier (current state-of-the-art levels). Such developments may, for example, include applications of new breeds, advances in precision farming, rotation optimization and GM crops (FAO, 2003; Smeets et al., 2007). In addition, agriculture could expand into saline and arid areas and explore opportunities for aquaculture (Federoff et al., 2010). It can thus be expected that yields in the WEC will develop at modest growth rates in the order of the past two decades. Unless the mentioned breakthrough innovations are implemented, growth rates may raise to levels reached in the 1960s and 1970s.

The general trends for the WEC and the CEEC show that a continuation of historic yield growth rates seems unlikely for both regions for distinctly different reasons. Given its yield gap, the CEEC is assumed to be able to raise their productivity by professionalization, improved management, *etc.*, similar to developments in the WEC in the second half of the previous century. As can be learned from the WEC example, such a catch-up strategy (Ball et al., 2004) would require a dedicated (agricultural) policy, supplying financial support to facilitate investments and reforming landownership. The adverse environmental pressures that resulted from intensification (e.g. by over-fertilization) in the WEC, until the 1980s, can be prevented by implementation of environmental legislation. Thus a leap-frog approach (Goldemberg, 1998) should be followed, copying those elements that have worked well in WEC.

3.5.3 Projected yield trends in literature

This section provides an overview of studies that have projected future growth rates (see Figure 3-5) for crop yields in Europe with the aim to assess the future land availability for bioenergy production.

The REFUEL study (Fischer et al., 2008) has projected yield developments for three groups of European countries; the Western European countries (WEC), the Central and Eastern European Countries (CEEC) and Ukraine (non EU). Projections were constructed for three scenarios. A base scenario assumes developments that are a continuation of the historic trend. The low scenario assumes an increase in organic farming in the WEC and a continuation of extensive farming in the CEEC. The high scenario assumes opportunities for the implementation of new breeds in the WEC while the CEEC is expected to intensify production towards WEC levels. Aggregate average yield growth rates are projected for the period 2000-30 for the three regions and are calculated at respectively 6-15% (WEC), 63-77% (CEEC) and 145-166% (Ukraine).

Ewert *et al.,* 2005) (Ewert et al., 2005) describe yield developments for Europe considering the EU15 countries Norway and Switzerland. Linear regression was performed on historic yield data for the period 1961–2002 (obtained from FAO). Projected changes in yields were modelled taking into account effects of climate change, increasing atmospheric CO_2 concentrations, technology development and these three factors combined. In addition projections are varied for future developments reflecting the IPCC SRES scenarios, considering a future emphasis on economy versus environment and global versus regional. Hence 16 development pathways are evaluated. Results indicate possible yield increases of 25% to 163% between 2000 and 2080. The variation in scenario projections diverges over time. As a reference, these outcomes correspond to projected yield increase of 29% to 61% by 2030.

A study by the EEA (EEA, 2006; EEA, 2007) estimates the bioenergy potential for the EU22 towards 2030. The aim of the study is to assess possibilities for bioenergy production, and along these lines agricultural productivity increases, without increasing pressures on the environment. The study therefore assumes dedicating land for extensive, environmentally oriented farming, securing land for protected nature and forest areas and allocating a fraction of intensively farmed land to set-aside area to accommodate ecological development. Average WEC yields are projected (EuroCARE, 2004) to change annually with 0.82, 1.12 and 0.62 % y^{-1} for wheat, rapeseed and cereals respectively. For the CEEC, there is considerably larger difference between crops wheat, rapeseed and cereals are expected to increase 0.02, 0.31 and 3.2 % y^{-1}.

The UN FAO (FAO, 2003) projects aggregate global yield developments and more detailed projections for the WEC and CEEC for the period 2001-30 (after (Bindraban et al., 2009) from personal communication with Bruinsma. Projections are based on a continuation of historic trends. Estimates for yield growth are provided for several crops such as oils, sugar and grains. For the WEC, yields are projected to change with 0.40, 0.93 and 1.17 % y^{-1} for oils, sugar and grains respectively. For the CEEC oils and sugar are expected to increase faster than in the WEC by 0.90 and 1.10 % y^{-1} for oils and sugar and slower for grains with 0.60 % y^{-1}.

Differences between yield growth projections between studies are significant. Therefore, it is interesting to compare these ranges with the historically observed growth rates (section 4.3). Together with the insights from the synthesis in section 5.1. some possible future pathways are examined, which place the projected growth rates into perspective by illustrating the policy measures that could be taken to reach projected yields.

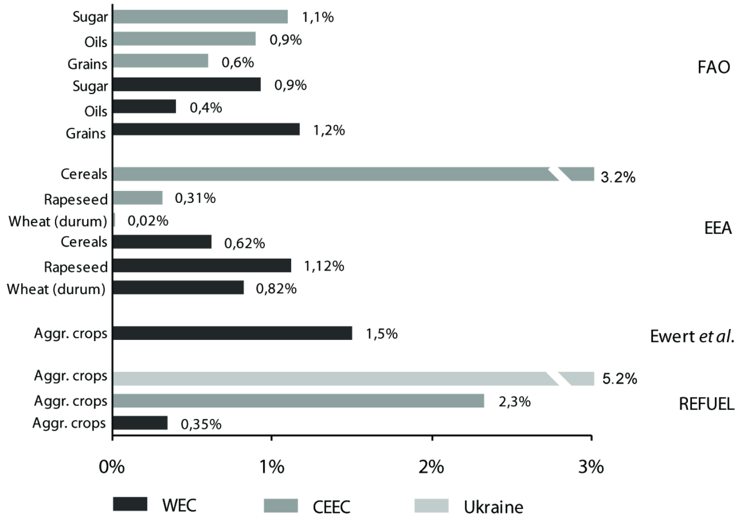

Figure 3-5 Average annual yield growth rate projections for Europe for the period 2000-30 for four studies (FAO, EEA, Ewert *et al.* and REFUEL).

Yield growth developments in the WEC at 0.5-1.5% y^{-1}, as assumed by FAO (0.8% y^{-1}), EEA (0.9% y^{-1}) and Ewert *et al.*(1.5% y^{-1}), are modest when compared to the historic developments between 1961-2007 but seem high compared to developments in the last two decades. Declining growth rates in the latter period, steered by an expansion in organic farming, set-aside obligations and a decoupling of production support, can be assumed to continue if these trends are unchanged. REFUEL projections (0.4% y^{-1}) for the WEC seem conservative in this respect.

Projected growth rates for the CEEC around 1% y^{-1} – as projected by FAO (0.9% y^{-1}) and EEA (1.2% y^{-1}) – seem modest when compared to average growth figures between 1961 and 2007, even more so when compared to growth rates prior to 1990 and past 2000. The Polish yield gap which is estimated at 45% (FAO, 2003) illustrates that there is ample agro-ecologic potential to improve productivities. Growth rates in the order of 2.5% y^{-1} and higher, as suggested by REFUEL (2.3% y^{-1}), have been reached during several periods for some crops in Poland. In addition, in the WEC growth rates in this range and higher have been reached, also over longer periods. Developments in the WEC in particular should be explained from the implementation of structural reforms in farm up-scaling (by re-allotment) and financial support to augment input levels. Ambitions for growth of this order for the CEEC should therefore be accompanied by stimulating policy, e.g. in the form of financial support. The EU's common agricultural policy (CAP) has shifted its focus from output maximization to improvement and maintenance of the land quality and rural identity. Therefore it can be questioned whether the current CAP does provide the level of assistance to farmers to bridge the existing yield gaps.

Ukraine (and the former USSR) shows a volatile historic trend which offers a weaker basis for a future outlook. A catch-up hypothesis, similar to that for Poland (and the CEEC) could be envisioned for Ukraine. Similarities are the existing yield-gap and the relatively low current input levels. The difference with the other CEEC is that Ukraine is not a member of the EU and hence does not fall under the agricultural support offered by the CAP. The REFUEL projections, originating from a catch-up assumption, for Ukraine seem very high in this respect. Although there have been periods that have shown annual increases of 5% and more, such periods are exceptions and are often reached when starting from (very) low levels and are always accompanied by stimulating agricultural policy mostly in the form of guaranteed intervention prices for farmers. Nevertheless, the potential is there.

3.5.4 Implications for land availability and bioenergy potentials

The growth rates projected in the studies discussed in the previous section work out differently in terms of the land that will become available for bioenergy production. Taking the agricultural land base in 2000 as a starting point the land that is freed-up until 2030 is calculated according to the growth rates presented in Figure 3-6. In the year 2000 the total agricultural land in respectively the WEC, CEEC and Ukraine amounted to 143 000, 58 000 and 41 000 km^2. Assuming the total output (related to food demand) of the land remains constant, all productivity increases result in land being freed-up, potentially available for the production of bioenergy crops. Following this reasoning Figure 3-6 shows the resulting land that is freed-up by 2030. All studies have considered the WEC, all but Ewert *et al.* have looked at the CEEC and only REFUEL considers Ukraine separately.

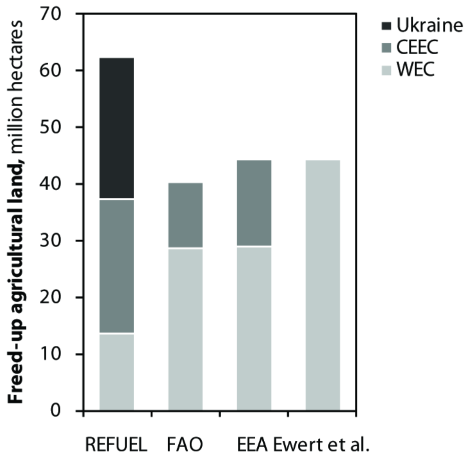

Figure 3-6 Implications of land availability and bioenergy production by 2030 according to yield projections of four studies.

Figure 3-6 presents the freed-up European land for four studies. At the extremes the regions WEC, CEEC and Ukraine are expected to be able to free up 14-44, 12-24 and 25 million hectares by 2030 respectively. This translates in a raw biomass potential from these freed-up lands by 2030, assuming an average yield (100 GJ ha^{-1} y^{-1}), of 5.1–9.3 EJ y^{-1}. Wide-scale implementation of high yielding (herbaceous) lignocellulosic crops could double the caloric output.

3.6 Discussion

For the analysis, selections had to be made to the data to keep the analysis workable. One simplification is the separate discussion of two groups of European regions, the Central and Eastern European Countries (CEEC) and the Western European Countries (WEC). Discussion of these groups of countries for example allows for the discussion of the macro-developments, such as the effect of supra-national agricultural policies, on productivity developments. On the other hand, it ignores the large diversity within these groups of countries. To analyse developments in more detail, the analysis focuses on four countries, two countries per group. Another selection was made with respect to the crops and livestock considered in the analysis. Wheat, sugar beet, rapeseed and cattle production were included. Outcomes show that crops within one country generally develop in the same direction and at equivalent growth rates. A more comprehensive selection of crops and livestocks could, however, have provided more conclusive outcomes for the development of yields in the overall European agriculture. A third simplification was the focus on a limited number of inputs to represent the overall use of production factors for the production of crops and livestock. Four inputs were considered: labour, machinery, fertilizer and pesticides. This selection for example does not differentiate between skilled and un-skilled labour, for developments in the increasing power per machine over time, *etc*.

This study presents aggregate developments for inputs and outputs. Although this provides insights in the general trends, the aggregation does not uncover individual driving forces such as efficiency, technical change, allocative change, which develop at different rates and possibly in opposite directions. Only the net result of all these drivers is captured. Multi Factor Productivity (MFP) analysis can quantitatively decompose productivity into its individual drivers. A preliminary investigation to use this method for this study showed that such an analysis was not feasible given the large data requirements, mainly because of the length of the period studied and the number of countries assessed. Future endeavors may consider applying an MFP approach to parts of the subjects studied (e.g. sub-sectors in countries). This could provide a more comprehensive insight in the specific role that individual driving forces have had on productivity developments. Analysis – and studies discussed – in this paper assume a linear development of absolute yield figures over time. From this assumption it follows that the (annual) growth rates decrease over time. This has limitations for extrapolating fixed annual growth rates into the future, especially over longer periods of time because the relative growth rates are based on different absolute yield levels.

3.7 Conclusions and implications

This paper has examined the extent to which biomass resources can be produced in Europe as a result of ongoing yield developments in agriculture. It assessed the driving forces behind, and the pace and direction of, agricultural yield developments in the past five decades in Europe. Furthermore, it explored how future yield pathways may develop under influence of economic and technological developments and policy deployment. The following conclusions are drawn:

- *Ongoing yield increases can open up an significant biomass potential on the short to medium term*

At the extremes the regions WEC, CEEC and Ukraine are expected to be able to free up 14-44, 12-24 and 25 million hectares by 2030 respectively. Assuming an average yield of 100 GJ ha^{-1} y^{-1} on these freed-up lands, this translates in a raw biomass potential of 5.1–9.3 EJ y^{-1}. Wide-scale implementation of high yielding (herbaceous) lignocellulosic crops could double the caloric output.

- *European yields have increased significantly over the last five decades*

Historic developments in European crop and animal protein productivity between 1961 and 2007 show an average mean annual growth rate of 1.6%. In relative terms, developments are slower on average in the Netherlands and France at 1.0% y^{-1} than in Poland and Ukraine (USSR) at 2.2% y^{-1}. In absolute figures, however, growth has been considerable in WEC and modest in the CEEC. As a consequence, the WEC has realized more of its agro-ecological potential compared to the CEEC which suggests a a considerable potential for yield growth in the CEEC.

- *Yields are actively steered by policy: significant yield changes realized over short time periods*

Results indicate a clear correlation between yield developments and the implemented agricultural policy, both in periods of positive and negative yield growth. In periods, and in countries, where stimulating policy (e.g. intervention prices) was implemented yields went up and reversely when stimulating policies were abolished yields contracted. Trend data show that significant yield changes can be realized over a short period of time. Outcomes hence suggest that productivity levels can be actively steered rather than being just the result of autonomous developments such as economic growth.

- *Yield growth did not always coincided with efficient use of production factors*

Periods of considerable yield growth have not always coincided with periods of high (output per input) efficiencies. For example, intervention prices have facilitated investments in production factors, leading to increasing yields but sometimes to lower output-per-input efficiencies because inputs were not used efficiently in the absence of an economic incentive. To the other end, environmental legislation that was introduced in the late 1970s, mainly in the WEC, incentivized the use of (restricted) inputs efficiently. These mechanisms illustrate the importance of appropriate policy to stimulate productivity while safeguarding efficiency and (related to this) sustainability.

From these conclusions some policy implications are derived:

- *Different stages of development require diverse policy needs for WEC and CEEC*

Possibilities to bridge the yield gaps in the CEEC depend on the agricultural policies that need to secure farm income levels, facilitate land reforms and safeguard environmental quality. Further developments of yields in the WEC may come from (breakthrough) innovations, improved management and technical progress.

- *Policy development for CEEC should include lessons from developments in the WEC*

Policies, particularly in the CEEC, could follow a leap-frog approach whereby past developments can give directions for developing future policies. Such policies may aim to increase agricultural output, increase yields, ensure efficiency and stimulate rural development. Policies that have stimulated agricultural output and yield increases are financial support to farmers and land ownership reform to facilitate up scaling. Other policy instruments have stimulated (resource) efficiency such as environmental legislation restricting input application and balancing demand and supply by quota systems and set-aside policies.

Acknowledgements

Jos Dekker (Utrecht University) is thanked for sharing his knowledge on historic developments in European and Dutch agriculture, in particular where it concerns (preservation of) nature areas. The help of Alfons Oude Lansink (Wageningen University and Research Centre) is acknowledged for providing insight in the opportunities and restrictions of economic multi factor productivity (MFP) methods. This study is conducted as a part of the Climate changes Spatial Planning Programme (Dutch: *Klimaat voor Ruimte*. The program is funded by the Dutch Government (Bsik subsidies for investments in the knowledge infrastructure), the European Commission and Stichting Shell Research.

4 Environmental impacts of integrating biomass production into European agriculture

Marc de Wit, Jan Peter Lesschen, Marc Londo & André Faaij

Submitted

ABSTRACT As energy crop production on European croplands expands, driven by accelerating consumption of bioenergy, there is a pressing need to evaluate the environmental impacts associated with this production. This chapter considers ongoing yield increases as a means of boosting agricultural output without needing to convert nature areas and grasslands to additional cropland. For nine land-use variants, the study evaluates cumulative greenhouse gas emissions (GHG) of N_2O, net organic carbon fluxes from soil and abated emissions achieved by replacing fossil fuels for transport with biofuels. The main finding is that, in European agriculture, it is possible to combine large-scale biomass production with food production sustained at current levels, without direct or indirect land-use changes and while accomplishing significant net environmental benefits. Maintaining the current agriculture results in 4.9 $GtCO_2$-eq. of cumulative N_2O emissions by 2030. Intensified food production and energy crop production on freed cropland in combination with mitigation measures can significantly reduce cumulative emissions for the annual crop groups of oil, starch and sugar beet to 1.9, 1.5 and 2.1 $GtCO_2$-eq., respectively. By 2030, perennial energy crop production can mitigate cumulative emissions for grass and wood crops to 3.3 and 4.5 $GtCO_2$-eq., respectively. The results indicate that research and policy efforts aimed at further increasing productivity can raise the output from existing European croplands while being able to reduce or mitigate emissions.

4.1 Introduction

Bioenergy consumption in Europe is accelerating, while agricultural output needs to be increased to keep pace with future global demand for food and biomass. Ideally, this increase should be accompanied by a reduction of the environmental impacts(Burney et al., 2009). Europe's environmental and biofuel policies (Commission of the European Communities, 2009) have stimulated biomass demand, which is to be met by a combination of imports and domestic production. Between 2005 and 2010, Europe's total primary energy production from biomass increased by 53%, from 3.0 to 4.6 EJ y^{-1} (EurObserv'ER, 2007; EurObserv'ER, 2010). Domestic European bioenergy resources are obtained from forestry, industrial and agricultural residues, and increasingly from dedicated bioenergy crop production. To increase dedicated biomass production further, additional land can be brought into cultivation (expansion) or aggregate yields in conventional agriculture can be increased through augmented input levels (intensification) and improved management (rationalisation). Cropland expansion, especially, is associated with direct and indirect land-use changes (i)LUC, such as the conversion of grasslands and nature areas into cropland with its related emissions (Overmars et al.). If bioenergy is to be a viable option for mitigation of greenhouse gases (GHG), these upfront emissions will need to be balanced with possible emission reductions due to fossil fuel replacement by biomass sources, which may lead to prolonged GHG payback times (Fargione et al., 2008; Searchinger et al., 2008; Al-Riffai et al., 2010; Lapola et al., 2010). Advanced biofuels, produced from cellulosic sources, are recognised to offer advantages over biofuels production from annual (sugar, starch and oil) crops, including with respect to their GHG reduction performance (Luque et al., 2008; Arvizu, 2010). Scarce land resources, undesired and uncertain direct and indirect impacts associated with cropland expansion, and Europe's proven track record of effective intensification have led the present study in line with other studies (European Environment Agency (EEA), 2006; van Dam et al., 2007; Dornburg et al., 2010; Faaij et al., 2010) to focus on possibilities for further intensification as a way to expand bioenergy use in Europe. The present study consistently evaluates the environmental impacts that may result from future land-use changes in Europe, which account for a gradual but large-scale intensification, coupled with gradual expansion of bioenergy production and soil management improvements.

Over the past six decades, Europe has successfully intensified its agricultural production. Although the coming decades pose serious challenges for securing food supply globally (United Nations Food and Agricultural Organization (UN-FAO), 2009), Europe's demand for food has stabilised, which offers opportunities for bioenergy expansion. The rapid agricultural intensification in Western European Countries (WEC) was achieved by various measures, including increased fertilizer and pesticide use, professionalization of farmers, up-scaling of agricultural holdings and use of high-yielding varieties (De Wit et al., 2011). As a result, between 1961 and 2007 wheat yields increased in France by 164% (from 2.4 to 6.3 t ha^{-1}) and in the Netherlands by 123% (from 3.8 to 7.1 t ha^{-1}). Central and Eastern European agriculture developed more erratically but with gradual growth until the late 1980s, followed by steep declines due to regime changes in the early 1990s and gradual recovery since then. For example, Polish rapeseed productivity increased by 64% between 1961 and 2007, starting from 1.6 t ha^{-1} (1961), peaking at 2.8 t ha^{-1} (1989), dipping to 1.6 t ha^{-1} (1996) and recovering to 2.7 in 2007 (FAOSTAT, 2010). Thus, for many crops significant yield gaps exist in central and eastern European countries (CEEC) (FAO, 2003; De Wit et al., 2011). Western Europe's intensification track-record, Central and Eastern Europe's current yield gaps, and projected higher demand for agricultural output forms the rationale of several studies (European Environment Agency (EEA), 2006; van Dam et al., 2007; Faaij et al., 2010) in hypothesizing a gradual convergence of CEEC yields to WEC levels as a way to boost agricultural output. The present study consider ambitious yield growth rates that are in line with rates observed in the past (De Wit et al., 2011). These higher growth rates for the CEEC and Ukraine lead to a gradual convergence of yields with WEC levels. At the assumed rate, complete convergence is achieved by 2050, which corresponds to CEEC yields reaching approximately 80% of WEC yields by 2030 (De Wit and Faaij, 2010; Fischer et al., 2010).

European agricultural intensification have succeeded in raising output, though not always in using resources efficiently and sometimes with negative environmental impacts. Increased fertilisation levels and over-fertilisation have led to eutrophication of ground and surface waters through leaching and run-off of nitrogen and phosphorus (Boyer et al., 2006). Since the 1980s, dedicated policy at EU level (Commission of the European Communities, 1991) and management changes by farmers have resulted in improved nutrient-use efficiency and reduced local water pollution (Erisman et al., 2008). This is confirmed by the absolute decoupling of agricultural production and fertilizer use: between 1990 and 2008, cereal and oil crop production in Western Europe increased by 18%, while nitrogen fertilizer consumption was reduced by 27% (FAOSTAT, 2010). As a result, over the same period, ammonia emissions decreased on average by 24% in the current EU-27 countries (European Environment Agency (EEA), 2010). This illustrates the importance of resource efficiency, especially when further intensification is considered.

Several studies have used various scopes and approaches to evaluate the environmental impacts of increasing agricultural output. Whereas some focus on agriculture for food production only (Smith et al., 2000; Smith et al., 2008; Burney et al., 2009), others evaluate the effects of integrating biomass production into agriculture (Melillo et al., 2010). The present study adopts the approach used in studies that focus on evaluation of net cumulative environmental impacts and applies it to land-use variants whereby large-scale biomass production is integrated into European agriculture.

The objective of this study is to evaluate the environmental impacts, particularly the net GHG balance, for nine-land use variants in Europe (see Figure 4-1). Our approach simulates four key developments: (1) gradual intensification of agricultural production, (2) gradual expansion of dedicated energy-crop production on cropland that has become available as a result of intensification, (3) implementation of structural management improvements such as reduced tillage, fertilisation improvements and increased carbon inputs to the soil and (4) the replacement of fossil fuels for transport with biofuels (see method section). The first land use variant (L) assessed considers the reference year 2004 (L1) representing the current agricultural land use. The impacts of mitigation measures (L2) and intensification (L3) are assessed separately and in combination (L4). Cropland that is gradually freed by intensification is assumed either to be left abandoned (L3, L4) or to be used for the production of five energy crop groups wood, grass, oil, starch and sugar (L5-L9). The primary result (see Figure 4-1) is the net mitigation balance in the period 2004-2030 for each land-use variant, specifying the emissions of nitrous oxide (N_2O), the net soil organic carbon (SOC) fluxes and the abated fossil emissions through biofuel use.

4.2 Results and discussion

4.2.1 Cumulative mitigation balances

Figure 4-1 shows the partitioning of the cumulative mitigation balance of greenhouse gases (black line) from 2004 to 2030 for N_2O emissions, net carbon sequestration and fossil fuel emissions abatement. The net soil organic carbon sequestration compared to the reference value in 2004 is assumed for a 20-year period which means that SOC sequestration occurs until 2024. At presumed agricultural intensification rates (L3-L9) (methods and Table S1), European food production can be confined to 156 million hectares by 2030 compared to the 204 million hectares currently cultivated (-24%). Together with 12 million hectares of fallow land, this will free up 60 million hectares not required for domestic food production by 2030. The land-use variants explored for this freed cropland are conversion to abandoned land (L3, L4) or conversion to energy crop production (L5-L9). Simulations for all the land-use variants evaluated (L2-L9) show a net reduction of cumulative emissions with respect to the current practice (L1). Emission mitigation is achieved through reduced N_2O emissions (L2-L4) and improved SOC sequestration (L2-L9) but mostly by emission abatement resulting from fossil fuel replacement by biofuels (L5-L9). Current (L1) annual N_2O emissions (see Figure 4-1) from European agriculture, when prolonged until 2030, accumulate to -4.9 $GtCO_2$-eq. Implementation of structural improvements to agricultural management at current intensity levels could reduce cumulative emissions by 31% (L1: -4.9→L2: -3.4). When yields are improved by increased fertilisation, emissions are reduced by a similar proportion, depending on whether mitigation measures are implemented (L1→L4; -45%) or not (L1→L3; -31%). Energy crop production on abandoned land (L5-L9) shows superior cumulative emission mitigation with respect to sustained food production (L1-L4). The production of energy crops on freed cropland cuts emissions not only through potential SOC sequestration but also by its potential to replace fossil petrol and diesel with bio-based transport fuels, thereby abating fossil-related emissions (see methods and Table S4). Cumulative mitigation of the annual energy crops oil, starch and sugar beet is of a similar proportion: cumulative emissions are roughly halved by 2030, from -4.9 (L1) to -1.9 (L7), -1.5 (L8) and -2.1 $GtCO_2$-eq. (L9). For perennial crops, cumulative emissions can be turned into net mitigation due to rapid and large abatement of fossil emissions and increased carbon sequestration. By 2030, net emissions of 4.9 $GtCO_2$-eq. are converted to net cumulative mitigation between 3.3 $GtCO_2$-eq. (L5, wood) and 4.5 $GtCO_2$-eq. (L6, grass). Perennial crops perform better because of: (i) reduced N_2O emissions due to higher fertilizer efficiencies and lower fertilizer requirements; (ii) higher SOC sequestration rates, achieved due to their deeper rooting systems and less ground disturbance by perennial crops; and (iii) higher GHG abatement potential given their higher yields (in terms of biomass and biofuel equivalents) and lower life-cycle emissions compared to fossil routes (see Table S4).

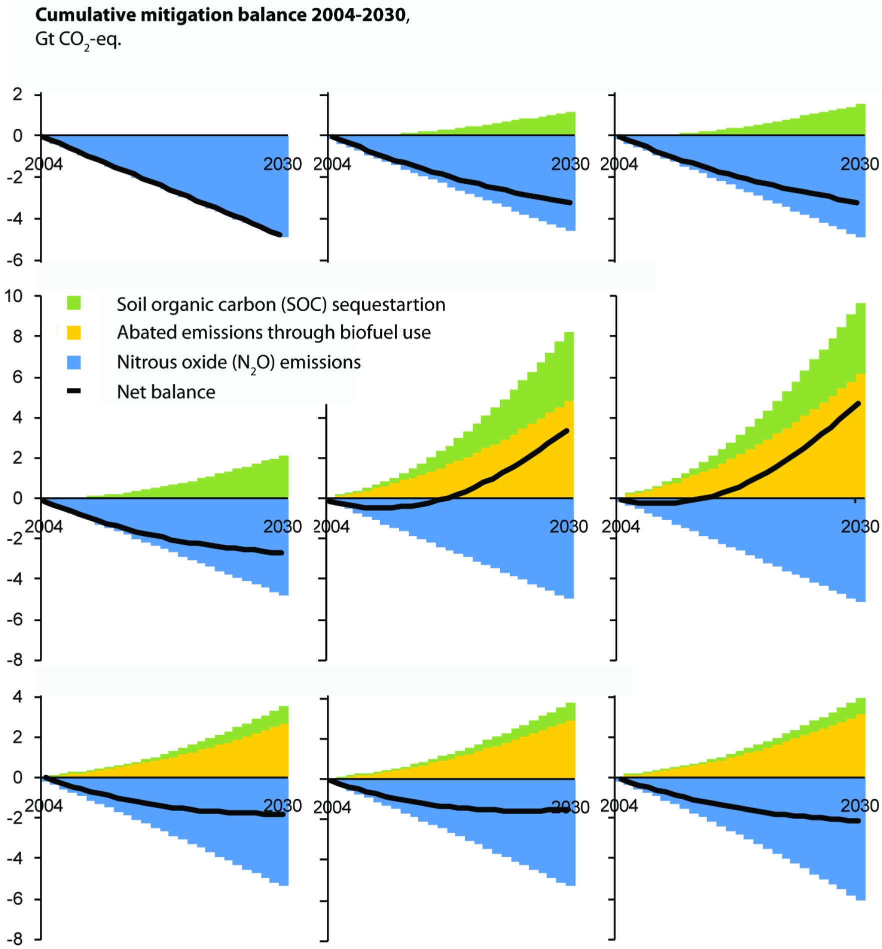

Figure 4-1 Partitioning of the cumulative mitigation balance of greenhouse gases in European agriculture from 2004 to 2030 for nine land-use variants (L1-L9), considering N_2O emissions (blue), net soil organic carbon sequestration (green), abated emissions through biofuel use (yellow) and the net balance (black line). Negative values indicate emissions; positive values indicate mitigations.

4.2.2 Per hectare nitrogen-carbon balance

Intensified production (L3-L9), established by advanced (balanced) nitrogen fertilisation, increases aggregate N_2O emissions per hectare compared to the reference value in 2004 (L1). Promotion of mitigation measures (see methods and Table S3) and changing land cover on freed cropland, allocated to fallow (L3,L4) or energy crops (L5-L9), stimulates soil carbon sequestration compared to the reference value in 2004 (L1). Implementation of mitigation measures (L2) only, such as the application of reduced tillage, sequesters modest amounts of soil carbon in comparison to when freed-up cropland is left abandoned (L3). Production of the annual energy crops oil (L7) and starch (L8) sequester modestly, sugar crops (L9) perform worse, but the perennial crops wood (L5) and grass (L6) perform best.

The net balance of N_2O emissions and carbon sequestration per hectare (see Figure 4-2, black dots) shows the relative performance of land-use variants. If Europe reforms its agricultural practice by aiming for emission reduction while sustaining current intensity levels, it could reduce GHG emissions due to agriculture significantly (L1→L2; -65%). The effect of only intensifying production without structurally improving management is of the same order as modernisation (L1→L3; -57%). Compared to sustaining current intensity levels with management changes, it would even perform far worse (L2→L3; 22%). Of the land use variants that only consider food production (L1→L4; -95%) and leave freed cropland abandoned, a combined approach involving intensification and implementation of management improvements cuts emissions most.

When the sole aim is to satisfy food demand, wide-scale adoption of mitigation measures is an effective way to cut emissions. In terms of cutting emissions (L2→L4), the additional benefit of intensification is modest and would therefore be hardly justifiable when food production is the end goal. What justifies and drives intensification to a far greater extent is the opportunity to expand production on freed cropland without iLUC. Expanded production on freed cropland has been evaluated for five land-use variants with large-scale energy crop production. Perennial crops outperform annual crops significantly in terms of emission mitigation, due to superior fertilizer-uptake efficiencies and higher net SOC sequestration rates. Whereas the perennial crops of wood (L1→L5; -143%) and grass (L1→L6; -140%) reduce emissions significantly, annual crop-land uses emit quantities approximately equal to the 2004 reference value – slightly lower for oil (L1→L7; -23%) and starch (L1→L8; -26%) and slightly higher for sugar (L1→L9; 6%).

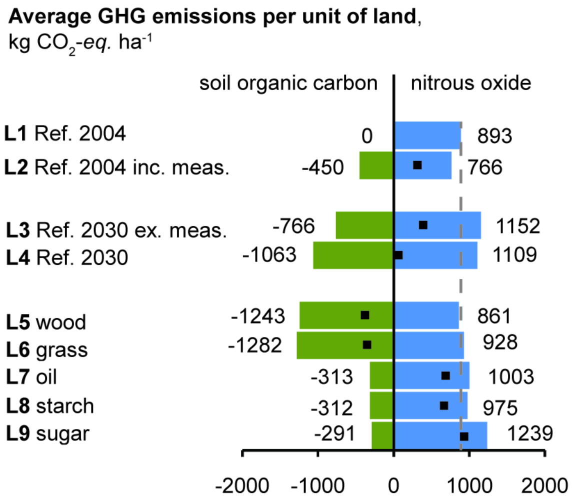

Figure 4-2 Per hectare emissions of nitrous oxide (N_2O), soil organic carbon (SOC) sequestration, and the net effect (black dots) for nine land-use variants.

4.2.3 Regional impacts

Assessing environmental impacts regionally (NUTS2) is particularly interesting for those impacts that influence the local environmental quality. Presented are regional changes to N leaching and runoff (see Figure 4-3 and appendix). Aggregate changes to N and P surpluses in the soil and regional changes to the soil carbon content are presented in Figure S4 and Figure S6 respectively. Emissions of greenhouse gases N_2O and CO_2 are less relevant to local assessment because they do not affect the local environment directly. Their contribution to global GHG concentrations, however, may have consequences on the regional level. Changes to SOC stocks in the soil, causing CO_2 emission or sequestration, can reduce or enhance the soil quality regionally (see Figure S6), which may affect various soil functions (D.S. Powlson et al., 2011).

Figure 4-3 shows the spatial distribution of N-leaching and runoff from soils for the reference situation (L1), and changes when balanced fertilisation and large-scale grassy energy crop production (L6) is applied. The current distribution of N-leaching and runoff levels shows a varied yet regionally concentrated picture. Generally, western European countries experience higher N-leaching and runoff levels than Eastern European countries. It is apparent from the changes in N-leaching and runoff that, in most regions, levels are reduced. Furthermore, a levelling of leaching and runoff levels is evident: regions with low levels show increases, while regions with high levels experience reductions. This levelling is a direct consequence of the assumed practice of balanced fertilisation by 2030. Lower general levels (in the lower map) can be explained by, in addition to balanced fertilisation, large-scale grassy energy crop production, which is particularly efficient with inputs. The general picture shown for grassy crops (L6) is similar for the other land-use variants evaluated, although slightly higher levels result from annual crops (L7-L9) than from perennial crop production (L5,L6), see Figure S4.

Nutrient surpluses of nitrogen (N) and phosphorus (P) can occur when they are leaked to the soil by leaching and runoff. The N and P surpluses in the soil and changes of these surpluses were evaluated the for nine land-use variants (see Figure S4). These changing surpluses result from adapted fertilisation practices. For annual crops, aggregated crop nutrient demand is supplied by the manure available in a (NUTS2) region, derived from regional livestock densities. In almost all regions, manure quantities are insufficient, in which case the remaining nutrient demand is met by mineral fertilizer. For perennial crops, only mineral fertilization is considered. P is only supplied to the land through manure application. With respect to the current situation (L1), N surpluses are reduced for all land-use variants (L2-L8), except in the case of sugar beet (L9). Reasons for this reduction are the application of balanced fertilisation and higher uptake efficiencies for perennial crops. P surpluses are reduced most when the freed cropland is allocated as abandoned land or to perennial crop production. For both cases, no manure and hence no P is (assumed to be) supplied to this land. Due to improved nutrient-use efficiencies (L2) and, on average, the less intensive fertilisation needed for oil and starch production, these land-use variants also show reduced P surpluses in the soil. Sugar beet has slightly increased P surpluses because its production requires relatively higher fertilisation rates.

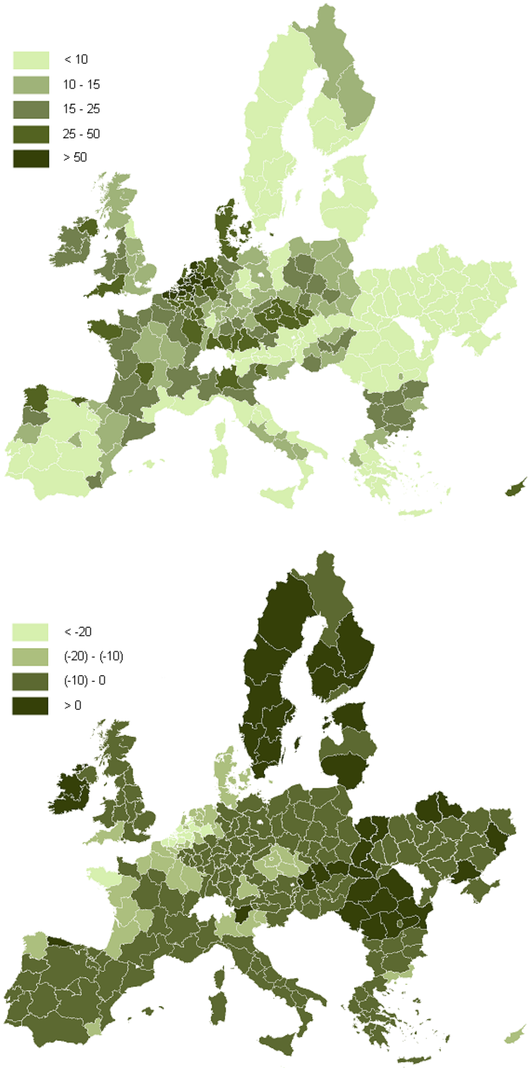

Figure 4-3 Spatial distribution of Europe's regional N leaching and runoff for the current land use (L1, left) and changes to N leaching and runoff when balanced fertilisation and large-scale grassy energy crop production is implemented by 2030 (L6, right). For an overview of all land use variants see *Figure S4*.

4.3 Discussion

Particularly critical to the outcomes are the assumed developments in European crop yields. It is assumed that these will increase towards 2030, especially in the central and eastern European countries and Ukraine, which should be able to close existing yield gaps to a large extent over the next two decades. Historical yield developments have shown that the assumed annual growth rates are feasible, though they require significant capital input and a dedicated agricultural policy (De Wit et al., 2011). If yields develop more slowly than simulated, fewer croplands are freed, restricting opportunities for energy crop production without iLUC and the ability to gradually reduce net GHG emissions by replacing fossil fuels. Another assumption is that the total output of food and feed produced domestically in Europe will remain constant over the coming decades. However, there may be reasons to increase or decrease future domestic production of food and feed, for example under influence of WTO polities, which would influence opportunities for energy crop cultivation in Europe accordingly.

There is considerable uncertainty in the modelled output stemming from input data, model structure, algorithms and parameters; for example, simplification of complex biochemical processes, generalisation of highly diverse agricultural systems and assumptions regarding future developments. Although these necessary simplifications of the model lead to uncertainty, its strength is that a uniform approach for all European countries enables a consistent and transparent assessment (Velthof et al., 2009). It is assumed that fertilisation of all crops will be balanced by 2030. For annual crops, this assumption comprises an over-fertilisation factor of 10% (cereals) or 25% (other arable crops) to account for N losses. For perennial crops, 100% efficiency is assumed (an over-fertilisation factor of 0%). In reality, both under- and over-fertilisation are common. Under-fertilisation restricts yields, whereas over-fertilisation increases N losses per unit of crop quantity that is produced.

The total mitigation potential due to management changes depends on two uncertain factors: (i) the rate at, and extent to which, measures are adopted; and (ii) the extent to which such measures can mitigate emissions. In this study, in order to explore the full potential of large-scale structural management improvements, it is assumed that Europe will achieve full implementation of measures by 2030. Whether this situation can be approached by 2030 depends on many factors, including agricultural policy. In addition, the assumption of no implementation in 2004 is an underestimation, as current agricultural practices already include some of the measures.

Assessing methane (CH_4) emissions caused by European livestock and dairy production was beyond the scope of the present study. To place the GHG emissions calculated in this study into perspective, they are compared to the projected CH_4 emissions of a previous study (Lesschen et al., 2009). The latter study projects that annual CH_4 emissions due to European livestock and dairy production would decrease from 285 to 255 $MtCO_2$-eq. between 2004 and 2030, while the total livestock herd would increase from 175 to 178 million over the same period. The number of beef and dairy cattle, which cause the highest CH_4 emissions, was expected to decrease over that period. For comparison: the projected annual CH_4 emissions of the reference study are slightly higher than the calculated annual N_2O emissions calculated for the reference land use variant in the present study. These projected values can be considered as conservative estimates, given that mitigation measures similar to those simulated for crop production in the present study can be considered for livestock production. Such measures could include: adapted feeding strategies to reduce enteric fermentation (e.g. through changes in feed intake and additives); and manure management (e.g. manure digestion and adapted stable designs).

There is also uncertainty regarding the emission abatement effect of agronomic measures. Mitigation measures may affect more than one GHG. While such a measure can reduce emissions for all gases, there may be a trade-off, in the sense that reduction of one GHG leads to increased emissions of another. For example, cover crops increase SOC but also pose the risk of increased N_2O emissions. Local circumstances such as climate and soil characteristics and management practices influence actual emissions. Also, the mitigating effect of measures may gradually change. For example, SOC sequestration occurs until equilibrium is reached, after which no net sequestration takes place. The IPCC assumes a default period of 20 years for reaching this equilibrium; however, for relatively cool regions it may take longer, whereas in warmer climate zones this equilibrium may be reached faster.

The GHG emissions prevented by replacing fossil fuels with biofuels are also uncertain, mainly because of two assumptions. Firstly, the European Commission's default values allocate the GHG emissions generated along the supply chain to the biofuel and co-products based on their energy content. Allocation of emissions according to various other product properties such as mass, market value, nutritional value or system expansion may increase or reduce the abatement values, depending on the supply chain considered (Hoefnagels et al., 2010). Secondly, the EC's default values relate input levels to default biomass yields that may differ from the (average) yield levels used in this study. Therefore, input values and resulting GHG emissions may deviate accordingly.

Comparing the outcomes of the present study to those of other studies is a complex process, mainly because of the differing assumptions regarding geographic scopes and future yield developments. Several studies that assess the European context assume static (Al-Riffai et al., 2010) or modest (European Environment Agency (EEA), 2006; Commission of the European Communities, 2011) future yield increases in Europe. Such assumptions – when combined with high EU biofuel mandates – inevitably imply that substantial imports of biofuels or feedstocks into the EU will be necessary. Ambitious emission-reduction targets in Europe thus increase the pressure on lands outside Europe, potentially leading to land-use change and associated impacts that may undermine the environmental viability of biofuels. However, the present study focuses on land-use variants based on the assumption that iLUC can be prevented by yield increases in order to fulfil Europe's potential for biomass production. Similarly to our study, another study (Fischer and Prieler, 2010) focussing on global developments, assumes considerable progress in increasing crop yields, which would greatly reduce the required conversion of nature and grasslands. Thus, their outcomes are also similar to ours: higher yields lead to higher GHG emissions per hectare; however, these are more than compensated by the abatement of emissions achieved by replacing fossil fuels with biofuels.

4.4 Methods

4.4.1 Modelling framework

MITERRA-Europe is an environmental assessment model that calculates nitrogen (N_2O, NH_3, NO_x and NO_3 see Figure S3) and greenhouse gas (CO_2, CH_4 and N_2O) emissions, as well as soil organic carbon stock changes, on a deterministic and annual basis, using emission and leaching factors. The model is used to assess effects of land-use and management changes on nitrogen losses, and interactions between these variables, on a regional (NUTS2) level for the EU27 (Velthof et al., 2009). For this study, the model was extended to include Ukraine. The inputs consist of activity data such as crop areas (FAOSTAT, 2010), spatial environmental data such as soil and climate data, and emission factors for nitrous oxide (N_2O) and methane (CH_4) (Intergovernmental Panel on Climate Change (IPCC), 2006), emissions of ammonia (NH_3) and excretion factors (Klimont and Brink, 2004). Leaching fractions were calculated by a refined method based on site-specific agro-ecological circumstances (Lesschen et al., 2009) (see SI appendix) instead of the IPCC leaching factor of 30%. Various new data were incorporated in the model: for the inclusion of Ukraine, agricultural statistics on oblast level (Ostapchuk, 2009) were added, as well as yield values for six perennial energy crops (miscanthus, switchgrass, canary reed grass, willow, poplar and eucalyptus) (Fischer et al., 2010).

An important source of nitrogen (N) emissions to the environment is applied mineral fertilizer and manure, especially when N application exceeds crop-removal rates. N_2O emissions occur in three ways: (i) direct soil emissions from applied mineral fertilizer and manure, crop residues and cultivation of organic soils; (ii) indirect soil emissions from leaching and runoff to ground and surface water and from volatilization and re-deposition of N; and (iii) emissions from animal faeces and urine in the field or housing. For mineral fertilizer, applied manure and crop residues, the N_2O emission factor is 1%; for grazing it is 2%. For indirect N_2O emissions, the emission factor for leaching and run-off is 0.75%; for volatilised and re-deposited N it is 1%. Furthermore, livestock contributes to CH_4 emission through enteric fermentation in ruminants and anaerobic digestion of manure during storage (Lassey, 2007). Methane emissions were derived from European regional livestock densities (Hoglund-Isaksson et al., 2010) and were the same for all year-2030 scenarios. Changes in land use and land management influence soil organic carbon (SOC) stocks (see Table S2). SOC content enhances various important soil functions such as water-holding capacity, nutrient retention and soil structure (D.S. Powlson et al., 2011). All GHG emissions are expressed in CO_2 equivalents (CO_2-eq.), based on estimates of the potential 100-year global warming values relative to carbon dioxide (CO_2: 1, CH_4: 25 and N_2O: 298) (Intergovernmental Panel on Climate Change (IPCC), 2006).

In the simulations assumptions were used with regard to crop yields, agricultural management and the degree of implementing mitigation measures (see Table S1). Crop yields for 2004 are based on actual yield statistics (FAOSTAT, 2010). The development of yields towards 2030 is given at the national level, assuming that yields in the CEEC and Ukraine will gradually converge towards WEC levels. The N fertilizer rate for 2004 is based on allocating the actual fertilizer consumption per country to crops according to their N demand. For 2030, balanced fertilisation is assumed, meaning that fertilisation is equal to uptake of the plant during growth, corrected by a crop-specific uptake factor. SOC sequestration is calculated as the difference between the initial SOC level in 2004 and the simulated SOC level in the 2030 scenario years, divided by 20 years, which is the default time that the IPCC assumes for equilibrium in SOC stocks after land-use or land-management changes. To evaluate the upper and lower limits of the impact of mitigation measures, either no implementation or full implementation is assumed.

4.4.2 Mitigation measures

Three types of mitigation measures were considered in MITERRA-Europe to simulate the effects on emissions of N_2O and soil organic carbon sequestration: reduced tillage, increased carbon input and fertilizer type improvements. Typical mitigation values are derived for the European situation based on a literature survey and parameterised for incorporation in MITERRA-Europe (Lesschen et al., 2009), see Table S3. The land-use variants (L2, L4-L9) for which implementation of mitigation measures is considered assume full implementation of all three measures together. Reduced tillage can promote SOC sequestration by limiting soil disturbance, which reduces decomposition by aeration. Although a positive effect of reduced tillage on SOC sequestration is confirmed in literature (Arrouays et al., 2002; Ogle et al., 2005), outcomes of its effect on N_2O emissions are inconsistent (Li et al., 2005; Meyer-Aurich et al., 2006; Chatskikh and Olesen, 2007), see Table S3. Increased carbon input to the soil entails a group of measures, typically including optimisation of crop rotations, the use of catch or cover crops, and the incorporation of crop residues. Catch or cover crops provide a temporary vegetative cover, which takes up N unused by the preceding crop, and after ploughing into the soil increases soil carbon content and reduces fertilisation requirements. Similarly, crop residues such as stubble, straw and other residues can be incorporated into the soil to add carbon. Although SOC content benefits from these measures (Arrouays et al., 2002; Li et al., 2005; Ogle et al., 2005; Meyer-Aurich et al., 2006), there is a risk of increased N_2O emissions (MacKenzie et al., 1997; Smith et al., 2000; Meyer-Aurich et al., 2006; Smith et al., 2008) due to the incorporation of additional N from crop residues. A change in the type of fertilizer used may reduce emissions of N_2O and ammonia (NH_3); such changes could include the replacement of urea-based by ammonium-based fertilizers, the application of slow-release fertilisers and the use of nitrification inhibitors (C.S. Snyder et al., 2009). Nitrification inhibitors prevent the turnover of ammonia into nitrate and can be applied to manure and mineral fertilizer. Slow-release fertilizers release nitrogen slowly, extending the uptake period with the aim of reducing N losses (McTaggart et al., 1997; Weiske et al., 2001; Velthof et al., 2002).

4.4.3 Fossil fuel emission abatement through biofuel use

Biomass resources produced on freed European cropland can be used for the production of biofuels to replace fossil fuels and thus to gradually reduce GHG emissions. In the present study, this potential abatement of GHG emissions is calculated for five biofuel routes for the crop groups: wood, grass, oil, starch and oil crops. The European Commission (EC) (Commission of the European Communities, 2009) has set typical and default abatement values for various transport biofuels, defined as the ratio of life-cycle emissions of the biofuel in question to those of the fossil fuels it replaces, excluding the net carbon emissions from land-use change (see Table S4). These values are based on typical supply-chain configurations and incorporate assumptions regarding input values.

Furthermore, the EC's typical values consider the GHG emissions generated along the supply chain to be allocated to the biofuel and co-products according to their energy content. Such typical values include N_2O emissions due to crop cultivation, which are assessed in greater detail in this study than those originally included in the EC values. Therefore, the original N_2O emissions have been deducted from the EC values and are replaced by the N_2O emissions calculated in this study in order to generate the results presented in Figure 4-1. Calculation of the annual and cumulative GHG emission abatement is based on the average energy-crop yields (De Wit et al., 2010; Fischer et al., 2010) and the biomass-to-biofuel conversion factors (Joint Research Centre (JRC), 2008).

4.5 Conclusions

Simulations indicate that, in European agriculture, it is possible to combine large-scale biomass production with food production sustained at current levels without iLUC and yet accomplish significant net environmental benefits. Intensification, at growth rates in line with historic observations, can gradually reduce the current 204 million hectares that are in cultivation for food production to 156 million hectares by 2030. Together with the 12 million hectares that already lie fallow, this frees up 60 million hectares that would not be required for domestic food production by 2030. The current net annual nitrous oxide emissions from agriculture of 182 $MtCO_2$-eq. would accumulate to -4.9 $GtCO_2$-eq. by 2030. All land-use variants evaluated in this study either reduce emissions or lead to net sequestration. Implementation of structural management improvement would reduce cumulative emissions by 1.5 to -3.4 $GtCO_2$-eq. by 2030. Large-scale energy crop production can reduce emissions and even lead to a net mitigation. In the case of grassy energy crop production, 4.5 $GtCO_2$-eq. could be mitigated by 2030. Nitrous oxide emissions will increase modestly due to higher fertilizer-application rates, though at improved efficiencies per unit crop quantity produced. Emission mitigation results partly from the temporary increase in SOC sequestration though mainly from replacement of fossil resources by biomass resources. The actual mitigations that can be realised in European agriculture critically depend on three preconditions that need to be met. (1) Gradual intensification of food production can reduce net emissions. The increase in N_2O emissions due to higher fertilizer application can be compensated mainly by dedicating freed croplands to extensive production practices such as leaving land abandoned or, ideally, producing biomass resources. (2) Such a gradual expansion of biomass production thus depends on the rate of intensification and the associated available cropland. Simulations confirm that the mitigation potential of biomass production on freed croplands is maximised when perennial crops are planted instead of annual crops. This is because perennials generally require less intensive management, have a higher fertilizer-use efficiency and generally have higher yields, both in terms of dry weight biomass and biofuel equivalents. (3) The implementation of structural improvements to agricultural management should be an integral part of any effort to intensify agriculture. In this respect, three measures that can immediately be implemented were evaluated and found to be effective: reduced tillage, soil carbon enhancement and more efficient fertilisation.

Acknowledgements

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4.6 Appendix : supporting material to Chapter 4

Conceptual framework

Figure S2 shows the conceptual approach used to assess the effects of agricultural intensification and mitigation measures on environmental impacts per unit of land and per unit of crop. Similar concepts are discussed in literature, e.g. by (de Wit et al., 1987; van Ittersum and Rabbinge, 1997). The graph shows how changes in intensity level are related to increased yields (top) and to changes in environmental impacts, with the effect of mitigation measures represented by a dashed line (middle). Relating yields and impacts per unit of land area (i.e. hectare) provides insight into the impacts per unit of crop (bottom). The letter symbols are referred to in discussing these dynamics. Figure S2 (middle) shows the environmental impacts for a crop at a relatively low intensity level (A), i.e. the reference situation. The dashed line indicates the favourable effect of implementing mitigation measures (A→B). Figure S2 (top) shows the relationship between intensity and yields. Higher inputs, improved management or a combination of both can increase yields (C→D), though marginal productivity increases gradually diminish as the intensity increases and ultimately become negative. However, changing input levels and management affects the environmental impacts (A→E). When an increase of the intensity level is accompanied by the implementation of mitigation measures the environmental impacts can be seriously reduced (E→F). When intensification is accompanied by mitigation measures, yields can increase (C→D), while environmental impacts can be reduced (A→F). Figure S2 (bottom) illustrates the conceptually optimal situations for minimizing environmental impacts per unit of crop quantity. In the case without mitigation measures, the optimum (G) is reached at a moderate yield (C), because aiming for a higher yield (D) will only increase the impacts (I). When intensification is accompanied by adequate management, the optimum shifts (G→J).

Modelling framework

Carbon stocks. The annual change in carbon stocks in soils (ΔC_{soils}) is calculated (equation S1) as the sequestration in mineral soils($\Delta C_{mineral}$) minus emissions from organic soils and due to liming:

$$\Delta C_{soils} = \Delta C_{mineral} - \Delta C_{organic} - \Delta C_{liming} \qquad (4.S1)$$

Mineral soils. The annual carbon changes in mineral soils are calculated (equation S2) as the difference in the soil organic carbon content (SOC in tC ha^{-1}) at two consecutive time points – now (SOC_0) and at some future time (SOC_T) – multiplied by the area in which the content applies (A in hectares) and divided by an inventory period (T in years). Thus, annual sequestration quantities are obtained. The default inventory period used in this study is 20 years, in accordance with the IPCC (Intergovernmental Panel on Climate Change (IPCC), 2006). The soil organic carbon (SOC) content (equation S3) is a function of a reference carbon content of the soil (SOC_{REF}), specified per climate and soil type (Intergovernmental Panel on Climate Change (IPCC), 2006), multiplied by three coefficients (see Table S1) that are related to the land use (F_{LU}), management (F_{MG}) and inputs (F_I).

$$\Delta C_{Mineral} = [(SOC_0 - SOC_T) * A] / T \qquad (4.S2)$$

$$SOC = SOC_{REF} * F_{LU} * F_{MG} * F_I \qquad (4.S3)$$

Organic soils ($\Delta C_{organic}$). Agriculture on organic soils leads to loss of carbon due to drainage and tillage, which enhance peat oxidation. Carbon emissions from organic soils on cropland and managed grassland are related to climate. The emission factors (tC ha^{-1} y^{-1}) for cropland and grassland in each climate region are 0.25 (cold) and 2.5 (warm) and 5 (cold) and 10 (warm), respectively. The area of agricultural organic soils on grassland and cropland was derived by overlaying the CLC2000 land-cover map (EEA, 2005) with the European soil map.

Liming (ΔC_{liming}). All carbon due to liming (i.e. applying limestone or dolomite to neutralise soil acidity) is assumed to be emitted. The emission due to liming (ΔC_{liming}) is calculated (equation S4) from the amount (M) of limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) applied to the soil and the respective emission fractions (EF), which are 12% and 13% for limestone and dolomite, respectively. Data on liming were derived from the national inventories of the EU-15 countries. For Mediterranean countries, zero liming was assumed because their soils have high carbonate content. For the new EU member states, the average of the EU-15 values is applied.

$$\Delta C_{liming} = M_{limestone} * EF_{limestone} + M_{dolomite} * EF_{dolomite} \qquad (4.S4)$$

Effects of mitigation measures on emissions and sequestration. Table S2 gives an overview of studies from which we derived the mitigation effects – on N_2O emissions and soil organic carbon (SOC) stock changes – of the three assessed mitigation measures: reduced tillage, increased carbon input and fertilizer improvements.

Nitrogen flows. Figure S3 is a schematic representation of the nitrogen flows simulated in MITERRA-Europe. Nitrogen is considered to be applied to the soil by applying manure from storage and during grazing, by applying mineral fertiliser, and by atmospheric deposition and fixation. Nitrogen applied to the land can be either emitted as gaseous N losses from the field, taken up by plants or lost through surface runoff. Nitrogen in the soil that is not taken up by plants can be leached below the rooting zone to the ground and surface water, or it can be subject to denitrification. Losses are simulated using emission factors and leaching fractions. For a detailed description of simulated flows and the factors and fractions used see Velthof et al. (2009) (Velthof et al., 2009).

Supplementary Tables:

Table S1 Assumptions as used in MITERRA-Europe regarding yields, agricultural management and the degree of implementing mitigation measures.

	2004	2030
Yields	Actual yields in 2004 for 34 food crops (FAOSTAT, 2010)	Projected yield levels; based on actual yields in 2004 and growth rates applied at national level[a]. WEC, on average 0.35% y^{-1}; CEEC, on average 2.3% y^{-1}, and Ukraine, 5.2% y^{-1}. Bioenergy crops: modelled yields (Fischer et al., 2010).
Agricultural management		
Mineral nitrogen fertilisation	Actual mineral fertilizer consumption in 2004 at national level (FAOSTAT, 2010), distributed among crops according to relative nitrogen uptake during growth.	Balanced fertilization: Balanced (nitrogen) fertilization provides fertilizer and manure according to the crop N demand after accounting for N inputs via atmospheric deposition, mineralization and biological N_2 fixation. The crop N demand was calculated as the total N content of the crop (= harvested part + crop residue) multiplied by a crop-specific uptake factor. This uptake factor was set at 1.0 for grass and perennial energy crops and 1.1 and 1.25 for cereals and other arable crops, respectively.
Carbon sequestration	Soil organic carbon (SOC) content in 2004 calculated according to land use, management and inputs (see SI appendix , for details).	Change in SOC content relative to 2004.
Degree of implementing mitigation measures	The reference 2004 (L1) assumes no implementation of mitigation measures. The reference incl. measures (L2) assumes 100% of mitigation measures implemented.	The reference in 2030 (L4) assumes full (100%) implementation of mitigation measures, as well as all energy crop land-use variants (L5-L9). The only exception is the ref. 2030, which explicitly excludes measures implementation (3).

A – Average country-specific yield growth rates between 2004 and 2030: Austria 31%, Belgium 14%, Bulgaria 92%, Cyprus 26%, Czech republic 67%, Denmark 34%, Estonia 113%, Finland 77%, France 27%, Germany 26%, Greece 24%, Hungary 65%, Ireland 59%, Italy 21%, Latvia 14%, Lithuania 125%, Luxembourg 103%, Malta 14%, the Netherlands 11%, Poland 67%, Portugal 40%, Romania 88%, Slovakia 79%, Slovenia 27%, Spain 39%, Sweden 49%, United Kingdom 26% and Ukraine 116% [17].

Table S2 Modelled effect of the three mitigation measures – reduced tillage, increased carbon input and fertilizer type improvements – on N_2O emissions and soil organic carbon (SOC) sequestration (see *Table S2* for details).

Measure	**Nitrous oxide (N_2O)**	**Soil organic carbon (SOC)**
Reduced tillage	No effect	2-8% SOC increase
Increased carbon input	Reduced fertilizer application (-5%) → reduced leaching and runoff (-10%) →increase in crop residue N (+5%)	4-11% SOC increase
Fertilizer-type improvements	15% reduction N_2O emissions from nitrate fertilizers	No effect

Table S3 European Commission typical abatement values for biofuels; the same values excluding N_2O emissions from cultivation; biomass-to-biofuel conversion factors and average European biomass yields.

	EC typical abatement value[a, b] *gCO_2 MJ_{fuel}^{-1} (%)*	EC typical abatement value excl. N_2O emissions from cultivation *gCO_2 MJ_{fuel}^{-1}(range)*	Biomass-to-biofuel conversion factors[d] MJ_{fuel} $MJ_{raw\ biomass}^{-1}$	Average European biomass yield[e] *GJ ha^{-1} (min-max)*
Wood	71 (76-93; 84.5)	78 (77-79)[d]	0.43 (0.38-0.48)	144 *(65 – 243)*
Grass	71 (76-93; 84.5)	78 (77-79)[d]	0.43 (0.38-0.48)	185 *(39 – 301)*
Oil	38 (45)	56	0.95	50 *(27 – 89)*
Starch	38 (45)	50	0.65	91 *(39 – 129)*
Sugar	51 (61)	56	0.79	71 *(43 – 135)*

A –Listed here are typical abatement values for the biofuel routes referred to by the European Commission and JRC (Joint Research Centre (JRC), 2008): 'sugar beet ethanol', 'wheat ethanol with natural gas as a process fuel in a conventional boiler' and 'rapeseed biodiesel'. For the crop groups wood and grass, both ethanol and Fischer-Tropsch diesel routes can be considered; therefore, this study uses the average of the EC's typical abatement values for 'farmed wood ethanol' and 'farmed wood Fischer-Tropsch diesel'.

B – As a reference value for fossil fuel emissions, the average of the emissions from petrol and diesel are used: 83.8 gCO_2-*eq.* MJ_{fuel}^{-1} (Joint Research Centre (JRC), 2008)

C – The N_2O emissions due to cultivation that are specified in the JRC WTT data (Joint Research Centre (JRC), 2008) have been deduced and replaced by the N_2O emissions calculated in this study.

D – Biomass-to-biofuel conversion efficiency factors as incorporated in JRC's well-to-tank (WTT) data (Joint Research Centre (JRC), 2008), used to calculate the default and typical abatement values for the biofuel routes listed in footnote a.

E – Average typical yields are derived from the total production potential (base case) by the year 2030 for the five crop groups (wood, 9.5 EJ y^{-1}; grass, 12.2 EJ y^{-1}; oil, 3.3 EJ y^{-1}; starch, 4.7 EJ y^{-1}; and sugar, 6.0 EJ y^{-1}). These values are divided by the area of European cropland on which the crops are produced: 66 million hectares (De Wit et al., 2010). The ranges indicate the average modelled European yields from marginally suitable soils (min.) and very suitable soils (max.), weighted for the amount of hectares that are available of marginally and very suitable soils (Fischer et al., 2010).

Supplementary Figures:

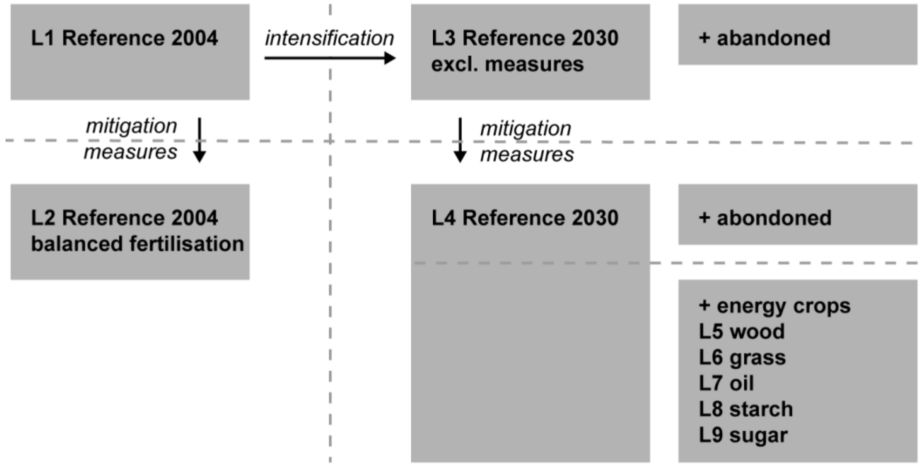


Figure S1 Overview of the nine explored land use variants (L1-L9).

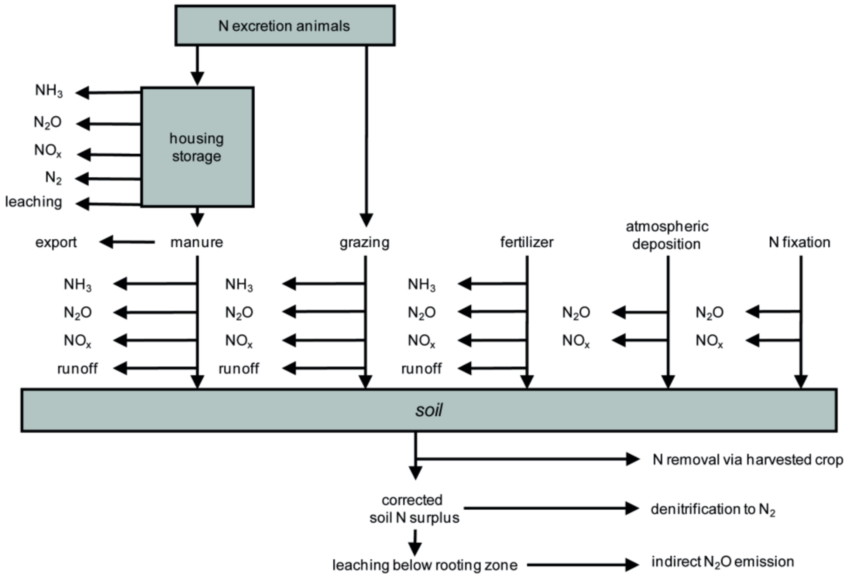


Figure S3 Schematic representation of nitrogen flows in MITERRA-Europe.

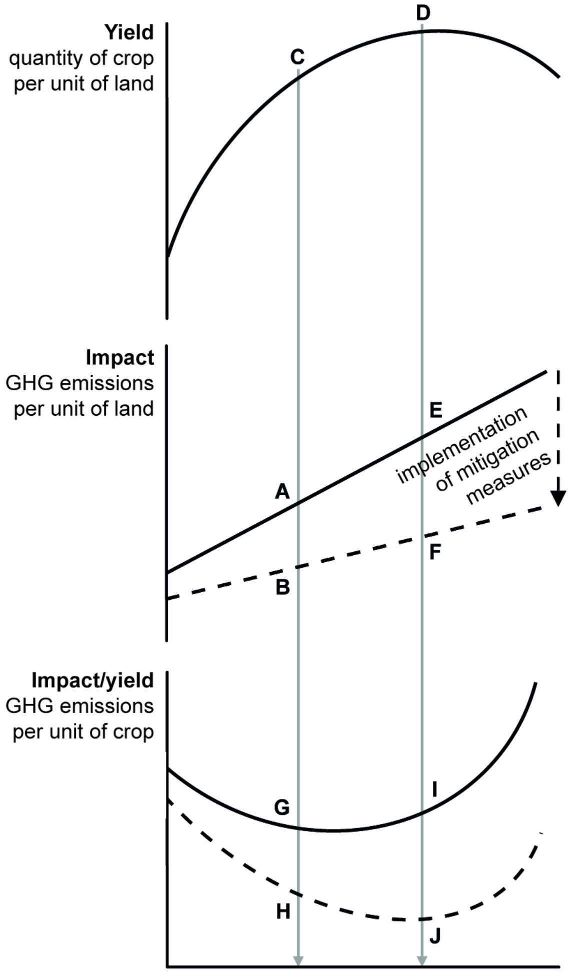


Figure S2 Conceptual representation of intensity-to-yield relationship (top); intensity-to-impact relationship and the potential reduction of impacts by implementation of mitigation measures (middle); the intensity-to-impact relationship (bottom).

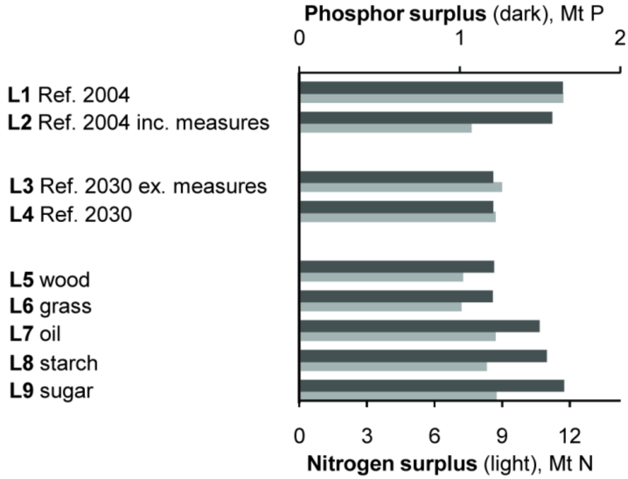


Figure S4 Aggregate nitrogen (N) and phosphor (P) surpluses in the soil for the nine land-use variants.

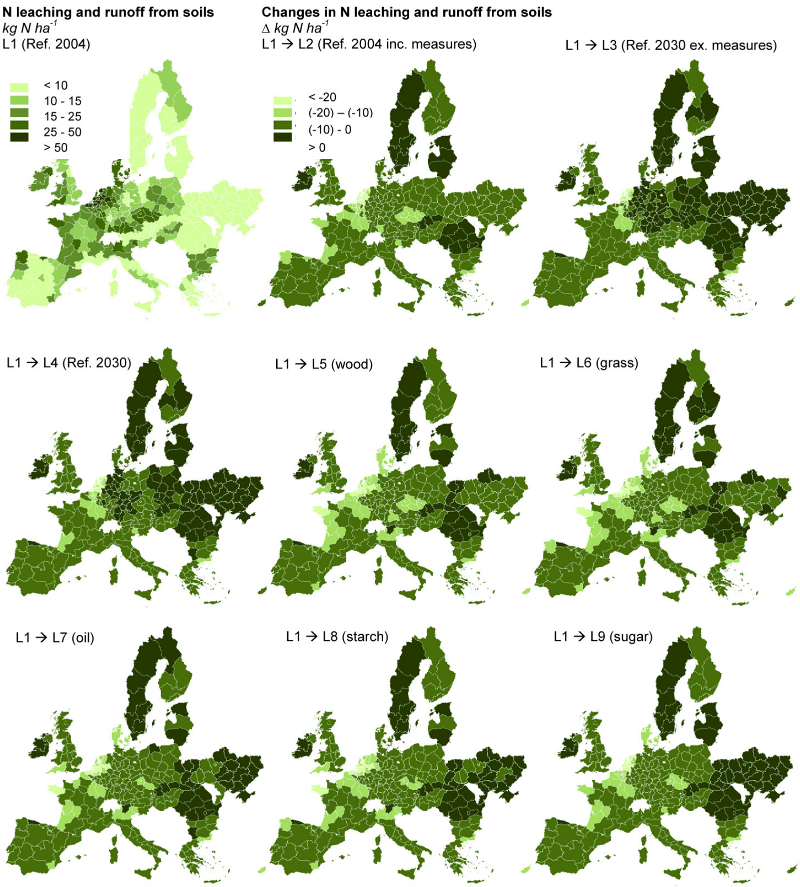


Figure S5 Spatial distribution of Europe's regional N leaching and runoff for the current land use (L1, upper left) and changes to N leaching and runoff for the remaining land use variants assesed (L2-L9).

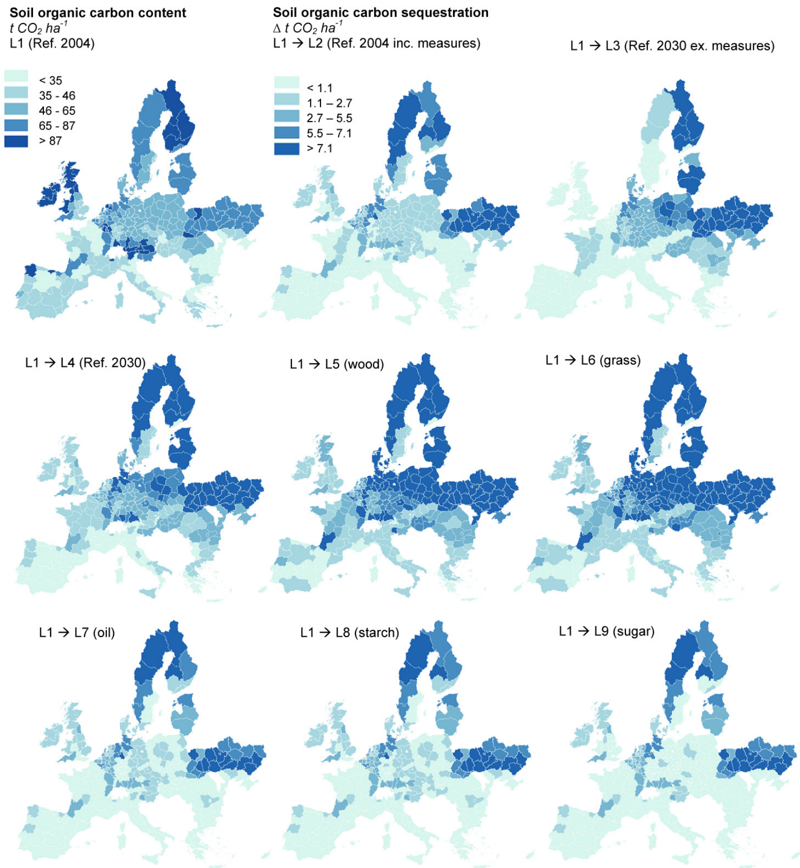


Figure S6 Spatial distribution of Europe's soil organic carbon content for the current land use (L1, upper left) and sequestration of soil organic carbon for the remaining land use variants assessed (L2-L9).

5 Learning in dedicated wood production systems: Past trends, future outlook and implications for bioenergy

Marc de Wit, Martin Junginger & André Faaij

Submitted

ABSTRACT This chapter assesses the learning potential of dedicated wood production systems to boost yields and reduce production costs. In particular, the chapter analyses past trends and provides a future outlook of developments in dedicated wood production for three cases: eucalyptus production in Brazil, poplar production in Italy and willow production in Sweden. A main objective of this chapter is to evaluate the extent to which experience curves can be devised for conventional woody plantation systems, and whether these can also be applied to SRC production systems.For current average short rotation cropping (SRC) production systems, Italian poplar shows the highest cost at 5.5 € GJ^{-1} followed by Swedish willow at 4.4 € GJ^{-1} and Brazilian eucalyptus is produced to the lowest costs at 2.8 € GJ^{-1}. It was assessed to what extent production costs can be reduced per step in the production cycle and how this affects the minimum cost levels that can ultimately be achieved. Ultimate cost reduction could lead to delivered costs of 2.2 € GJ^{-1} for poplar, 1.9 € GJ^{-1} for willow and 1.9 € GJ^{-1} for eucalyptus on better quality lands. Based on historic cost data and production trends, experience curves were applied providing progress ratios for poplar in Italy and eucalyptus in brazil. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The extent to, and rate at, which cost reductions can occur within the next 20 years were evaluated by combining current costs, minimum cost levels and progress ratios with ranges in European and global biomass demand projections. This shows that, at the assumed growth rates for biomass production in Europe and for global production, minimum cost levels can be reached within the next two decades for all cases.

5.1 Introduction

The production and use of wood resources expands globally, increasingly for energy applications. Main drivers for its use as a source of energy are diversification and the mitigation of energy related greenhouse gas (GHG) emissions through substitution of fossil fuels. At present, important applications for solid bioenergy include domestic and district heating and co-firing in power plants. Potential future uses include (advanced) biofuels production and biobased chemicals and materials (IPCC, 2011). These fuels and chemicals will to a large extent be produced from lignocellulosic biomass from forests and dedicated plantations.

Global productive forest plantations amounted to 109 million hectares by 2005, increasing at a rate of 2.0 million hectares per year during the 1990-2000 period and at 2.5 million hectares per year from 2000 to 2005 (FAO, 2006). Market conditions in the global wood industry are changing: for example forest plantations supply an increasing share of total forest products and an increasing competition for wood fibres between the energy industry and the traditional forest industry is observed (Nilsson and Bull, 2005). One particular development has been a global increase in short rotation cropping systems for energy use. These systems rely on high density planting, rapid growth and short harvesting cycles (typically 1 to 7 years). SRC may refer to herbaceous crops such as miscanthus and switch grass and woody species like pine, poplar, willow and eucalyptus (IEA, 2009).

Short rotation crops (SRC) are species and cropping systems selected and optimised for their fast growing and high yielding characteristics. These crops are produced around the globe for example willow is produced in the Sweden, the UK, the US and Poland; eucalyptus is produced in Brazil, India, China and India and poplar is produced in China, India and Italy.

The continued deployment potential for woody biomass sources critically depends on how technological learning proceeds and subsequent cost reductions are established as these can improve the economic competitiveness and thus market share of bioenergy systems compared to fossil and other renewable options (de Wit et al., 2010). Analyses that relate technological learning and cost reductions to the degree to which a technology is utilized can be quantified using experience curves. A comprehensive overview of existing literature on experience curves for fossil and renewable technologies is provided by Junginger *et al.* (Junginger et al., 2010), including bioenergy applications (Hamelinck et al., 2005; Junginger et al., 2006; de Wit et al., 2010). De Wit *et al.* (2010) (de Wit et al., 2010) illustrated the strong influence of learning rates of different biofuel production routes (in Europe) for their respective deployment. Data on perennial cropping in that analysis were based on crude assumptions only. Three recent studies have analyzed cost reductions in cropping systems for US corn (Hettinga et al., 2009), Brazilian sugarcane (van den Wall Bake et al., 2009) and German rapeseed (Berghout, 2008). These studies found progress ratios, the rate at which production costs can be reduced with every cumulative doubling of established production, of 55, 68 and 80% respectively.

Similar assessments for dedicated perennial wood cropping systems are lacking. Challenges exist with regard to data quality, consistency and level of detail. Because dedicated wood production for energy is still limited, data are scarce and more fragmented than for the annual crop cases mentioned. To deal with this, analyses could rely on data from the production of wood for conventional applications such as for timber and fibre, for which established industries exist that have been producing for many decades. Limitations exist, however, due to the different requirements for differing applications such as to straightness, thickness, density and cellulose content. These different demands influence the cultivation system with respect to coppicing, rotation periods, fertilization requirements, harvesting and hence influence production costs.

A main objective of this chapter is to evaluate the extent to which experience curves can be devised for conventional woody plantation systems, and whether these can also be applied to SRC production systems. Typically, a key methodological challenge in experience curve analysis is related to the choice of system boundary (with regard to time frame and geographic scope). The impact of these choices on the results will be investigated in detail. Furthermore, the present paper aims to provide an overview of past developments, the current status and an outlook of costs and yield developments in dedicated wood production systems for energy. It provides a review of quantitative data and identifies the driving forces that have shaped past developments. To evaluate the future cost reduction potential for dedicated wood cropping systems, both bottom-up insights and top-down approaches (including experience curves) are combined and applied to global and European demand projections to sketch scenarios for future deployment of SRC systems and possible developments in production costs.

Section 2 describes the methodologies that are used, the methodological challenges encountered and specifies the data gathering efforts. Section 3, gives an overview of SRC cropping systems and specifies the specific systems assessed in the present study and present bottom-up cost breakdowns. Section 4 starts with an overview of past developments in wood production systems, applies experience curves to them and derives progress ratios. Next, cost reduction options and the preconditions to achieve those are applied to current average cost levels and derives minimum cost level that can ultimately be achieved. The progress ratios are applied to European and global demand projections to analyze how fast and when minimum cost levels can be reached. Finally, in section 5, the outcomes are discussed and conclusions are drawn.

5.2 Methodology

To assess future developments in SRC wood production systems, a main aim of the present paper was to construct experience curves based on past production costs and produced volumes. This approach was found to be difficult as a result of data limitations. In order to explore the opportunities for performance improvements and sensitivities in SRC production systems the present study contains three methodological steps. Firstly, an overview is given for current average bottom-up production costs and yield levels and, based on bottom-up data-review, minimum cost levels are derived. Secondly, historic developments in the performance of these systems are assessed in order to specify developments in production cost levels and yields and to derive first order estimates for progress ratios of those systems. Thirdly, Future prospects for cost reduction are explored by assessing the rate at which cost can decrease by linking the derived progress ratios to global and European demand projections. Verification with bottom-up derived minimum cost levels allows to explore if and when these levels are reached.

5.2.1 Data gathering and challenges

Data availability for SRC wood production systems is more constrained and fragmented compared to annual cropping systems, for several reasons: fewer statistics are recorded by (inter)national statistics bodies; data are often not (made) publicly accessible; companies operate the entire value-chain and rely on bilateral trade contracts instead of trading on the market (no commodity market), *etc*. For all cases, it was found that knowledge institutes that collaborate with and are involved in R&D developments for the industry provide the richest source of information. Primary data were collected through field research at knowledge institutes in Brazil (State University of Campinas, Brazil), Italy (Consiglio per la ricerca e la sperimentazione in agricultura (CRA), Casale Monferrato, Italy), Sweden (University of Agricultural Sciences, Uppsala, Sweden) and Poland (Institute for Fuels and Renewable Energy, ECBREC, Warsaw, Poland). Field research involved conducting expert interviews and collection of data from (the archives at) these institutes and national statistics of these countries.

5.2.2 Bottom-up cost analysis and minimum cost levels

Bottom-up cost data are presented for the typical current cultivation and management practices. Cost breakdowns distinguish between establishment, maintenance, harvest and local transport. Costs are discounted and presented for normalised annual per hectare costs per step of the production cycle, including ranges in these costs (see Table 5-2). These cost levels are linked to average current yield levels to derive per gigajoule production costs. Possibilities and options for improvements in cultivation and cost reductions (summarized in Table 5-3) are obtained from expert interviews and literature review and quantified whenever possible. Based on this inventory the total improvement potential and ultimately minimum cost levels are quantified.

5.2.3 Top-down cost analysis: experience curves

An experience curve approach can be applied to analyze historic cost developments, assuming that the performance of a cropping system (i.e. production costs) changes by a fixed fraction with every doubling of established production or exercised activity (cumulative volumes of wood produced) (Boston Consultancy Group (BCG), 1968). Comprehensive literature exists on the principles, applications and verification of this method (Junginger et al., 2010). The experience curve can be expressed as a power law:

$$C_t = C_o\ (P_t/P_o)^b \tag{5.1}$$

Where C_t is the unit production cost at a future time t; C_o is the initial unit cost at the start of (commercial) production t=0; P_o is the cumulative production at an initial start of (commercial) production; P_t the cumulative production at a future moment. A progress ratio (PR) can be derived that expresses the costs after one doubling in cumulative production. The PR can be derived from the learning rate b: PR = 2^b. The uncertainty of the curve fit is reflected by the progress ratio error (σ_{PR}); as described by van Sark (Van Sark, 2008) after Bevington (Bevington, 1969).

Four key examples that have successfully applied an experience curve to historic cost developments of annual crops used for biofuels are highlighted:

- Brazilian sugarcane production for ethanol has achieved a 60% cost reduction between 1975 and 2004, resulting in a progress ratio of 68% (van den Wall Bake et al., 2009).
- Similarly, US corn production saw a cost reduction of 63% in 30 years, resulting in a PR of 55% (Hettinga et al., 2009).
- Rapeseed production in Germany for diesel shows similar figures with production costs declining 70% between 1971 and 2006, the equivalent of a PR of 80% is found (Berghout, 2008).
- For wood fuel supply chains from primary forest residues in Sweden a PR of 87% was found (Junginger et al., 2005).

The analysis of annual cropping systems in these studies relies on extensive and consistent data sets that for several decades have been recorded by (inter)national statistics bodies (e.g. Eurostat, Faostat, USDA (USDA/NASS, 2011)) to keep track of the status and progress of the agricultural sector.

A main methodological challenge in experience curve analysis is related to the applied system boundary, both in time and geographic scope, for which calculated progress ratios are particularly sensitive. Determining the first (unit of) production is complex because the early phases of production are often poorly recorded. In the case of Brazil, the period that lies between the start of eucalyptus production and large-scale commercial production covers more than a century. For poplar production no statistics were available from the early years of production. Learning systems are often not restricted to national settings. Therefore, to assess sensitivities, progress ratios were derived both by applying cost reductions to national and to global production volumes, at least for the case of eucalyptus. A mechanism that stimulates performance improvements is knowledge and technology spill-over between similar crops produced in different countries or between different crops produced in the same country. In many cases, technologies in their initial development are only produced in a single country, and it thus suffices to account for the national cumulative production. However, as soon as the same technology is also produced or implemented in other countries, ideally the joint (global) cumulative production should be used when devising experience curves. Taking again the example of eucalyptus production Brazil, this is difficult to determine, as eucalyptus has also been produced in many other world regions, yet specific experiences (e.g. the use of eucalyptus for the production of charcoal for steel making) is limited to Brazil. To address the sensitivities of choice of geographical scope, different biomass demand projections for national or global developments are used when evaluating how rapidly minimum cost levels can be reached.

5.2.4 Exploring minimum cost levels and development rates: top-down versus bottom-up

To explore the extent to, and pace at, which production costs can go down, the bottom-up and top-down outcomes are combined. The application of progress ratios to demand projections can give an indication at what speed future costs can decline. However, simple extrapolation can result in impossibly low projections for cost levels. Bottom-up cost analysis, on the other hand, can provide insight into the improvement potential of every step of the production cycle and derive minimum cost levels, but can in itself give very limited information on the potential speed of development. A combination of these approaches is recommended for realistic projections for future cost developments, see (Junginger et al., 2010). Related to this issue is the notion that experience curves assert that the PR is fixed for a production system through different stages of technological maturity (Junginger et al., 2010). Empirical findings suggest (Arrow, 1962; Carlson, 1973) that at some point of technological maturity (for example when the turning point in the S-shaped market diffusion curve (Rogers, 1962) is reached) the experience curve flattens and PRs will increase. These dynamics emphasize the importance of understanding the fundamental driving forces and limitations for cost reductions, which is why these aspects are combined in the analysis (Lensink et al., 2010).

5.3 Production settings, costs and historic developments

5.3.1 Cropping systems

Table 5-1 presents an overview, for the three cases, of the climatic conditions, the cropping system configurations and applications for which wood is produced. Short rotation crops (SRC) are species and cropping systems selected and optimised for their fast growing and high yielding characteristics. SRC can either be grown as single-stem crops or as a multiple-stem crop in which case, after a first harvest, the crop's coppices (willow) are harvested. When optimised for achieving maximum yields, and depending on being a single or multiple-stem crop, SRC are typically harvested after 1 to 7 years of planting (IEA, 2009).

Three types of eucalyptus plantations are considered for Brazil: (large-scale monoculture) plantations either produced as (1) single stems or (2) coppiced in SRC production systems and (3) agro-forestry systems. Coppiced production was initiated for the production of bioenergy feedstocks operating higher plant densities. Agro-forestry systems produce eucalyptus at modest plant densities combined with food crops (mainly rice, soy and maize) and livestock grazing when trees get bigger. Agro-forestry plantations are often practiced by out-growers; farmers that are contracted by industries to produce eucalyptus. Willow production is only considered for SRC production, optimized for calorific output, produced in coppiced form at high plant densities. To stimulate sprout formation willow is cut back, depending on the species, in the first, second or third year after planting (Abrahamson, 2002). Poplar production is either produced for traditional applications such as for construction and paper and pulp or as an SRC crop for energy.

Table 5-1 Production characteristics for the production SRC poplar in Italy, eucalyptus in Brazil and willow in Sweden.

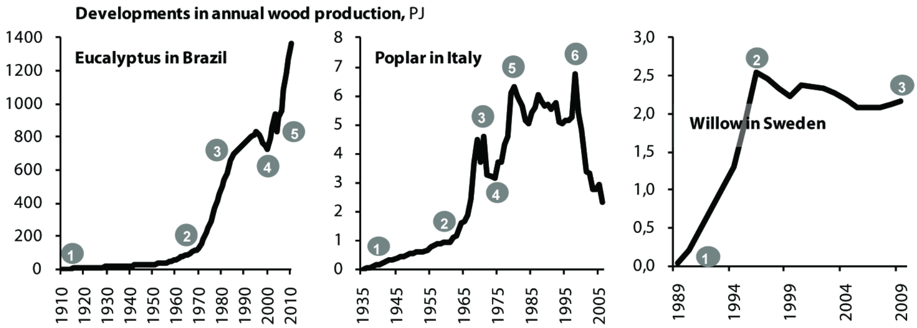
	Eucalypt			**Poplar**		**Willow**
	Mono-culture Single stem	*Agro-forestry*	*SRC*	*traditional*	*SRC*	*SRC*
Cases						
Country	Brazil			Italy		Sweden
Climatic zone(s)	(sub)tropical, temperate in South			Temperate and Mediterranean, alpine in North		Temperate, subarctic in North
Production system						
type	Stem	Stem	Coppice	Stem	Stem / coppice	Coppice
Plant densities *(plants ha^{-1})*	~ 1 500	~ 100	~ 1 100 – 2 200	~ 300	~ 10 000	~ 12 000
Lifetime of plantation *(yrs)*	15 – 21	15 – 21	8 – 12	10 – 15	10 – 15	10 –21
Rotation length *(yrs)*	5 – 7	5 – 7	2 – 3	10 – 15	1 – 5	1 – 3
Biomass applications	Paper and pulp, iron and steel (charcoal), timber	Timber	Energy	Plywood, sawing wood, particle board, paper and pulp	Energy, paper and pulp	Energy (electricity, heat and biofuels)

5.3.2 Sector developments

Figure 5-1 presents the produced wood quantities over time for poplar in Italy (Lopéz-Legarreta, 2009), willow in Sweden (Van Hulst, 2008) and eucalyptus in Brazil (Van den Bos, 2010). Number symbols in the graphs indicate events and developments that led to changes in production volumes, these are further discussed below. In addition, these figures are used to derive cumulative production quantities that are use in section 4.1. to fit experience curves.

Brazilian eucalyptus. Sizeable eucalyptus production in Brazil started in the beginning of the 20th century. Developments were gradual until the late 1960s after which it accelerated to peak at almost 4 million hectares in the mid 1980s. It then dipped at 3 million hectares around 2000 and has since then been growing and breached 4 million hectares in 2007 (Bacha, 2007). While the introduction of eucalyptus production in Brazil was in 1824 (1) the first industrial plantations were established in the 1900s (De Andrade, 1939) to provide fire wood, telegraph poles, sleepers for railway companies and lumber for new towns along the railroad (Andrade, 1939). (2) The production of high grade bleached pulp for paper making started in the 1940s. Next to plantations in São Paulo state, plantations expanded to the state of Minas Gerais for charcoal production, supplying to the iron and steel industry (Bacha, 2003). (3) By 1966 nearly half a million hectares of eucalyptus plantations were established, 80% located in the state of São Paulo (Mora and Garcia, 2000). In that year, a reforestation program (PIFFR) was launched to secure forest supplies for the decades ahead, mainly for charcoal and paper and pulp production. As a result, production increased to 6 million hectares by 1988 (Bacha, 2006). (3) In addition, in 1974, after the oil crisis the federal REPEMIR program aimed at substituting imported fossil fuels by forest products. The program, providing financial support, mainly boosted expansion in regions where land prices were low in the central-west and south-east. Production in these regions was unsuccessful due to low water availability that restricted yields while its remote location drove-up transport costs . Learning from this experience, the sector professionalised aiming for a better transfer of knowledge, technologies and methods. For example by improving selection criteria for the optimal species given site-characteristics, improving the silviculture and genetic improvements to optimise plant characteristics. (4) During the 1980s, forestry companies sought expansion of their production by contracting local farmers (out-grower schemes). While foresters could expand the resource output, farmers generated an additional and fixed income. From the 1990s increasing concerns about adverse effects of large-scale monoculture forestry such as erosion, nutrient runoff and wildlife habitat loss were addressed with the introduction of certification schemes, like FSC, through the implementation of integrated forest management practices.

Figure 5-1 Developments in the production of poplar in Italy (ISTAT (Istituto nazionale di statistica), 2011), willow in Sweden (Helby et al., 2006; Statistiska centralbyrån (SCB), 2010) and



eucalyptus in Brazil (Associacao Brasileira de Celulose e Papel (BRACELPA), 2007). Number symbols in the graphs indicate events and developments that led to changes in production volumes, these are further discussed below.

Italian poplar. Poplar production in Italy (ISTAT (Istituto nazionale di statistica), 2011) developed erratically; starting around 1935, production increased until the late 1970s, stabilising during the 1980s and gradually declining afterwards until 2006. While traditional plantations are operated since production began, SRC plantations started operation only around 1994 (Facciotto, 2009). (1) By the 1930s demand for wood increased for which the production and supply of poplar became the industry standard. (2) After the war, economic recovery spurred the demand for wood resources for furniture, packaging and particle board for construction until the end of the 1960s. (3) Subsidies in the form of price guarantees for food crops made poplar less profitable and more risky compared to food production which stalled and even reduced poplar production in the 1970s. (4) The oil crises drove up fossil energy and raw material commodity prices, boosting profitability and hence production of poplar for the plywood and chipboard sector. (5) In the 1980s a reorganization in the plywood industry, triggered by increased competition with particle board for the furniture industry, caused a decline in poplar production. This decline in the number of farmers active in poplar production was accelerated by stricter environmental regulation such as restricted fertilization levels. Early

1990s, wood prices strongly devaluated because a change in waste legislation from then on allowed discarded (waste) wood to be used in the chipboard industry. Although at the same time the demand for wood pellets for energy use increased, this only stabilized poplar production since most of that particular demand was met with imported conifer wood. The 1990s also saw the first use of poplar production for electricity generation purposes by the large utility ENEL. (6) Since 2000, production has continued to decrease due to a strong volatility in wood prices, putting the profitability of production under pressure. This situation worsened when a financial aid scheme initiated by the Italian government, which successfully increased the area under poplar production, was abolished shortly after because it was found to be incompatible with EU regulations.

Swedish willow. Commercial willow (Salix) production in Sweden started in the early 1990s increasing fast, peaking in 1996 at 16 thousand hectares, declining afterwards and stabilizing at around 14 thousand hectares to the present day. Optimized for calorific output, willow is produced in coppiced form at high plant densities. Though the amount of land under willow produced has increased since the 1980s, production is still small scale. (1) Starting in the 1980s, Salix production in Sweden received attention for its potential use as an energy crop. In 1984 research grants stimulated the research, development and deployment (RD&D) in Salix breeding, leading to the development of clones with improved characteristics such as higher yields and frost resistance (Christersson and Sennerrby-Forsse, 1994; Helby et al., 2006). Apart from the potential of energy crops to replace fossil fuels, it offered an attractive alternative to replace conventional agricultural crops.(2) As a result of reforms of EU's common agricultural policy (CAP) and a Swedish reform (Omställning 90) in the early 1990s, financial support was cut e.g. intended to reduce cereal production. To offer an alternative, subsidies were granted in Sweden to farmers who switched from cereal production to other land uses, including Salix. Quite many of the farmers that switched were older farmers that wanted to reduce their working hours on the farm. Boosted by these subsidies, by 1996, 16 thousand hectares of Salix were established (Silveira, 2001). The 1990s reform had been the initial step in a process aiming at deregulation of farm support and transforming to a more market oriented agricultural sector. The process slowed when in 1995 Sweden joined the EU and farmers were eligible for CAP support when cross compliance criteria were met. This again stimulated cereal production and leaving land fallow. On top of subsidies for the switch to and establishment and production of Salix as an energy crop, fiscal incentives and subsidies were introduced to stimulate the purchase of biomass fuelled combined heat and power systems (CHPs) or the retrofitting older systems (De Visser, 2004) although this apparently did not stimulate further growth of willow production.

5.3.3 Cost breakdowns

Table 5-2 shows the production costs for the three cases for average current SRC cultivation and the ranges in these values. The ranges identified in the values stem from deviations from average cultivation practices e.g. due to site-specific circumstances and from opportunities to improve. These latter improvement options are summarized in Table 5-3. Figure 5-2 summarizes the cost breakdown of the current average production systems. Italian poplar shows the highest cost followed by Swedish willow; Brazilian eucalypts is produced to the lowest costs. For poplar in Italy, five 2-year rotations are considered for a 10 year plantation lifetime at a plant spacing of 10 000 plants per hectare generating 14 t ha^{-1} y^{-1}. Production costs at the plant gate amount to 5.5 € GJ^{-1} (Coaloa and Vietto, 2005; Bergante and Facciotto, 2006; Facciotto, 2009), including the opportunity cost of land 0.26 € GJ^{-1} and the cost for local transport 0.5 € GJ^{-1}. Swedish SRC willow plantation operates seven 3-year rotations at a plant density of 12 000 cuttings per hectare which generates an average of 10 t ha^{-1} y^{-1}. Delivered production costs amount to 4.2 € GJ^{-1} which includes considerable costs for local transport at 1.0 € GJ^{-1} and the opportunity cost of land at 0.26 € GJ^{-1}. A typical Brazilian eucalyptus plantation in the state of Minas Gerais operates three 6-year rotations at a plant density of 1600 plants per hectare and generates a gross yield of 820 m^3 over the 18 year plantation lifetime, equivalent to 18 t ha^{-1} y^{-1}. Production costs for such a configuration amount to 2,8 € GJ^{-1} (CIF (Centro de Inteliência em Florestas), 2007), including 0.5 € GJ^{-1} for local transport costs and 0,1 € GJ^{-1} opportunity cost for land. Further cropping systems specification are described below.

Brazilian eucalyptus. For eucalyptus, land prices have increased slightly in recent years and show large regional variation. While in most states land prices averaged 800 to 2400 € ha^{-1}, the state of São Paulo experienced prices of up to 4000 € ha^{-1} (CIF (Centro de Inteliência em Florestas), 2009). Prices for seedlings and cuttings can differ distinctly depending on the species, genetic quality, size of order, distance to market, production efficiency of the nursery, condition of the seedlings, *etc.* The majority (70-80%) of fertilizer is applied at the plantation setup (Melo-Sixel and Mariani Gomez, 2009). Prior to planting, calcium and magnesium is applied to improve the soil structure, neutralise soil acidity and stimulate microbial development. Next, the nutrients phosphorus, nitrogen, potassium and boron are applied in holes around the plant. Finally, the same nutrients are applied to the soil cover. Pest control is the single highest contributor to the costs of setup and maintenance and involves operations to combat insects, mainly ants and termites. Costs are about equally distributed among the costs for pesticide inputs and their application to the field. Other maintenance costs include construction of fire lanes, technical assistance and taxes and fees. Harvesting costs are related to the mechanization level of harvesting operations which in turn is related to the plantation size. Transportation costs for local transport for example from the field to a sawmill depend on transportation distances, vehicle type, road conditions and loading times.

Italian poplar. The purchase costs of land in Italy varies considerably, due to regional variability in land scarcity, but mainly because of variation in the opportunity cost of land (Schönhart, 1998) depending on the competing land use, e.g. suitable agricultural land versus set-aside land. In southern European settings Gasol *et al.* (Gasol et al., 2009) estimates opportunity costs of 0.15-0.50 € GJ^{-1}. Establishment includes tillage, land refining, fertilization and weed control (Facciotto, 2009). Fertilization during set up involves application of phosphorus and potassium whereas nitrogen fertilizer is applied mainly at regular intervals during growth. Plantation maintenance involves similar operations including tillage (e.g. pruning, harrowing and weeding), pest control, fertilization and irrigation. The timing, frequency and extent of these activities varies according to site, silviculture, plantation scales, level of professionalization (Coaloa et al., 2005). Irrigation is common but levels depend on local water shortages and management

(Coaloa et al., 2005). Harvesting of the coppices takes place every 2 to 3 years (Bergante et al., 2006).

Swedish willow. Production of willow in Sweden for bioenergy use started in the late 1980s. Rosenqvist *et al.* (Rosenqvist et al., 2005) argue that the land purchase price does not properly reflects the costs of land. Instead, they suggest to use the opportunity costs as a more adequate measure for land costs associated with willow production. They estimate these costs to be approximately 0-0.5 € GJ^{-1} at present and 0-0.4 € GJ^{-1} in the future. Planting of willow is carried out by a large Swedish agricultural contractor (Lantmännen) who coordinates the planting process; acquiring the cuttings and planting them, operating a one-step planting machine. Typical per hectare nitrogen fertilization is advised at 70 (±10) kg N in the first year, 110 (±10) kg N in the second year; no application in the third year (Gustafsson et al., 2007). Phosphorus and potassium application is rare, although low-cost waste streams containing those nutrients are applied in some cases. Harvesting equipment is used that cuts the stems and chips them directly (Larsson, 2007). After harvest, wood chips are loaded onto 120 m^3 containers at the road side. Moisture content after harvest and at the time of transport is approximately 50% which is the upper limit that district heating plants can handle. In most cases transport is arranged by the same contractor that takes care of harvesting and that negotiates selling prices with buyers, mainly power plant owners.

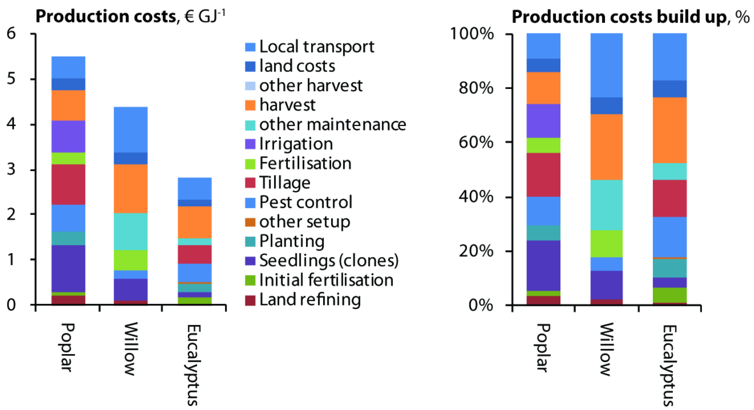


Figure 5-2 Breakdown of average current production costs for cultivation of poplar, willow and eucalyptus for harvest, the (opportunity) costs of land and the costs for local transport (left) and the relative contribution of the production steps to the overall costs (right). Based on data presented in Table 5-2.

Table 5-2 Discounted annual production costs per hectare per step of the cropping system for current management for eucalyptus, poplar and willow.

Production cycle steps	Costs[a, b] per activity					
	Eucalyptus		**Poplar**		**Willow**	
	value	range	value	range	value	range
Yield (t ha^{-1} y^{-1})	18.2[j,]	17 - 20	14	9 – 18.5	10[o]	6 – 12[o]
Setup						
Land purchase (€ ha^{-1}) or opportunity costs (€ GJ^{-1})	*4000[i] (pur-chase)*	*1600 – 4000[i]*	*0.25[h] (Oppor-tunity)*	*0 – 0.5[h]*	0.25[h]	0 – 0.5[h]
Land refining (€ ha^{-1} y^{-})	*3[j]*	-	*32[c]*	*32 – 39[c]*	9.5[t]	3.8 – 11.9[t]
(initial) fertilisation (€ ha^{-1} y^{-1})	*16[j]*	*6 – 25[l]*	*7[c]*	*7 – 14[c]*	39[u]	0 – 85[u]
Seedlings or clones (€ ha^{-1} y^{-1})	*12[j]*	*4 – 11[l]*	*168[c]*	*75 – 168[c]*	*See plant-ing*	
Planting routine (€ ha^{-1} y^{-1})	*20[j]*	-	*50[c]*	*45 – 50[c]*	41[q]	38 – 43[q]
Other setup (€ ha^{-1} y^{-1})	3[j]	-	-		3	-
Maintenance						
Pest control (€ ha^{-1} y^{-1})	*45[j]*	*31 – 95[m]*	*93[d]*	*76 – 110[d]*	17[s]	10 – 21[s]
Tillage (€ ha^{-1} y^{-1})	*43[j]*	-	*144[d]*	*129 – 159[d]*	-	-
Fertilisation[d] (€ ha^{-1} y^{-1})	*see setup*	-	*46[d]*	*32 – 60[d]*	*See pest control*	
Irrigation (€ ha^{-1} y^{-1})	-	-	*112[d]*	*0 – 218[d]*	-	-
Other maintenance[f] (€ ha^{-1} y^{-1})	*18[j]*	-	-	-	0.81[r] (GJ)	-
Harvesting (€ ha^{-1} y^{-1})	75[j]	58 – 98[n]	108[e]	60 – 150[e]	95[p]	24 – 95[p]
Local transport (€ t^{-1} or € GJ^{-1})	0.49 (GJ)[k]	0.28 – 0.69[k]	0.5 (GJ)[f]	0.15 – 0.5	17.5 (t)	16.6 – 18.4

NB – Yields are discounted in the calculation of production costs. The yields presented in the table are not discounted yields.

A – All costs in Euros are reported for the year 2010. Costs and prices are assumed to be the yearly average of the year in which the study was published unless reported otherwise. Cost figures were converted between currencies and over time in two steps. Firstly, values were corrected for inflation or deflation (to December 2009) in the currency in which costs were stated. Secondly, values were converted to Euros applying the exchange rate for December 2009 (Oanda.com, 2011).

B – Discounted cash flow analysis was applied to calculate the (net) present value to the first year of the plantation to account for the unequal distribution of costs and revenues over the plantation lifetime. Revenues (benefits) of wood plantations exist mainly of the harvested wood after subsequent rotations. The primary interest in the present study is to derive the discounted production costs rather than net profits which would involve the inclusion of market prices to which harvested wood could be sold at the time of harvest. To account for the monetary value that the physical harvest represents at the moment of harvest, physical streams are also discounted. Ample literature exists on the subject of discounted cash flow analysis for wood plantations, e.g. see (Smeets et al., 2009). The discount rates used were 10% for Brazil and 7% for Italy and Sweden.

C – Establishment costs for poplar are based on personal communication by Pablo Lopez with mr. Gianni Faccioto in 2009 (Facciotto, 2009). Costs were specified for typical short rotation forestry (SRF) plantation of 7 000 plants per hectare for a 10-year plantation, presented under 'value'. No variation in the costs were specified for the SRF plantation setup costs. Therefore, as an indication for the cost range the costs for traditional plantations, from the same source, are presented under range, sometimes as the lower limit and sometimes as the higher limit. Land refining: sums the cost for ploughing and a step referred to as additional land refining.

D – Maintenance costs are based on Coaloa (Coaloa et al., 2005). Apart from specifying values, cost reduction estimates are given for chemical pest treatment, soil management and fertilisation of 31%, 19% and 47% respectively, without specifying a timeframe over which this could be realised. The typical cost values are considered to represent the high-end of costs. Improvement options the 'value' refers to the average of these two.

E – Harvest costs: based on Bergante (Bergante et al., 2006).

F – Transport costs are based on Gasol (Gasol et al., 2009) who reports cost indications for transport per gigajoule.

G – Yields are based on Bergante (Bergante et al., 2006).

H – Rosenqvist *et al*. (Rosenqvist et al., 2005) suggest to use the opportunity cost of land as a measure of land costs. They estimate the opportunity cost of land for willow production in Sweden at between 0 and 0.5 € GJ^{-1} currently and between 0 – 0.4 for the future. These same values were used for Italy.

I – The costs of land were taken from a study by Centro de Inteliência em Florestas (CIF (Centro de Inteliência em Florestas), 2009). While in most states land prices averaged 800 to 2400 € ha^{-1} the state of São Paulo experienced prices of up to 4000 € ha^{-1}. The cost of land varies considerably depending on land quality and proximity to facilities and end-use markets. Purchase costs were depreciated over three plantation lifetimes of 21 years to make them comparable to the (opportunity) land rents that were used in the other cases.

J – the costs of eucalyptus production are mostly based on a study by Centro de Inteliência em Florestas (CIF (Centro de Inteliência em Florestas), 2007) who reports on the costs of eucalyptus production for a typical Brazilian plantation in the state of Minas Gerais operating three 6-year rotations at a plant density of 1600 plants per hectare and generates a gross yield of 820 m^3 over the 18 year plantation lifetime, equivalent to 18.2 t ha^{-1} y^{-1}.

K – The costs for local transport were based on personal communication at STCP in 2009 (STCP, 2009). Costs are specified per tonne kilometer (t km) for two transport distances: at increasing distances the costs per t km decline. STCP estimates costs at 0.30 R$ $(t\ km)^{-1}$ below 50 km and 0.12 R$ $(t\ km)^{-1}$ at distances over 150 km. More than half of all transport was under 100 km in 2008 (Associacao Brasileira de Celulose e Papel (BRACELPA), 2007).

L – Centro de Inteliência em Florestas (2008) (CIF (Centro de Inteliência em Florestas), 2008) estimates a variation in the costs for fertilizers, harvesting and transport that depend on the level of mechanization and inputs that are applied. Based on the ultimate range provided by CIF (2008) the extremes are determined relative to average management and input levels this results in a ±61% variation.

M – Included in the pest control are the costs for weeding. Van den Bos (Van den Bos, 2010) reports the costs for weeding, after (CEDAGRO, 2009), distinguishing between chemical and manual and weeding, which varies between 99 and 300 R$ ha^{-1} y^{-1} respectively.

N – The low end of harvesting costs, based on personal communication by Arno van den Bos with mr. Seixas in 2009 (Seixas, 2009), is estimated at 10 $R\$_{'09}$ m^3. A high estimate of 17 $R\$_{'09}$ m^3 was based on personal communication at STCP in 2009 (STCP, 2009; Techelatka, 2009).

O – Christersson (Christersson et al., 1994) estimates yields of 6-8 t ha^{-1} y^{-1} when extensively managed and 10-12 t ha^{-1} y^{-1} when intensively managed on commercial scale plantations.

P – Harvesting costs increase with higher yields. Based on expert interviews and supplemented with findings from Lantmannen a range of 350-550 € ha^{-1} per rotation of three years was found. The lower estimate is based on (Giglera et al., 1999; Larsson, 2007) who expect that when improved harvesting equipment is commercially produced in series it can be produced to one-fourth of the current costs.

Q – Planting of 12 000 plantings is considered. Costs are not specified for the plantings and the planting operations.

R – Costs for other maintenance were taken from Rosenqvist et al., 2005 who specifies costs (in € GJ^{-1}) for brokerage (0.25), administration (0.15), restoration (0.04) and overhead (0.37).

S – Total costs were presented for weed control and the application of potassium and phosphorus fertilizers in all but the years when crops are harvested. An average amount of 45 € ha^{-1} y^{-1} was reported and a range of 25-55 € ha^{-1} y^{-1}.

T – The costs for operations performed before every planting (pre-planting) include ploughing, harrowing and herbicide (glyphosphate) application. Reported costs were 200 € ha^{-1} and a range of 80-250 € ha^{-1}.

U – Costs were reported for nitrogen fertilization 200 € ha^{-1} per rotation with a range of 0-432 € ha^{-1}. At the lower end no fertilisation was considered.

5.4 Past and future performance

5.4.1 *Historic developments*

Considerable increases of yields in Italian poplar and Brazilian eucalyptus production were observed in the past (see Figure 5-3). In Sweden, no sizeable yield improvements were observed, although variations in yield levels exist between high and low intensity production systems. Production costs per ton which are strongly affected by yield increases show a similar picture: significant cost reductions for poplar and eucalyptus and modest developments in Sweden. Below, for each case observed cost reductions and yield developments are discussed in more detail. For Italian poplar an experience curve was fitted to the historical data. For Brazil a progress ratio was estimated on limited data and thus comes with considerable uncertainty.

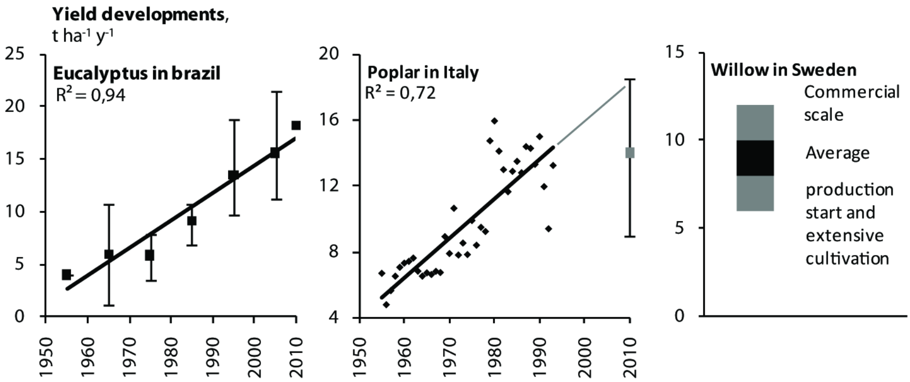


Figure 5-3 Yield developments in wood production for poplar, willow and eucalyptus.

Brazilian eucalyptus. Yield developments, based on linear regression (Betters et al., 1991; Campinhos, 1999; Pereira de Rezende et al., 2005; Hoeflich, 2006; Garlipp, 2008), suggest an average yield increase between 1955 and 2010, from 3.1 to 17.4 t ha^{-1} y^{-1} (see Figure 5-3). Several studies estimate average yearly eucalyptus yields around 20 t ha^{-1} y^{-1} (SBS (Sociedade Brasileira de Silvicultura), 2001; IPEF (Instituto de Pesquisas e Estudos Florestais), 2008; ABRAF (The Brazilian Association of Forest Plantation Producers), 2009; Melhoramentos, 2009). Yield increases resulted especially from technological development, species selection with optimal characteristics and genetic improvements made to species (Campinhos, 1999). Bottom-up cost data on Brazilian eucalyptus production are scarce, despite the long production history. Nevertheless, a progress ratio is estimated based on this limited data set. Pereira de Rezende (Pereira de Rezende et al., 2005) estimate average cost developments for eucalyptus production on *cerrado* in the state of Minas Gerais between the 1960s and 2005. Discounted per hectare, production costs show a 66% decrease over that period, from 14.1 to 4.8 k€ ha^{-1} for a 21 year plantation, excluding the costs of land and local transport. The observed 66% cost decrease over four decades is in line with what was found for annual cropping systems (Berghout, 2008; Hettinga et al., 2009; van den Wall Bake et al., 2009). The bottom-up costs for 2007, presented in Table 5-2 correspond to a cost of 4.2 k€ ha^{-1} for a 21-year plantation (CIF (Centro de Inteliência em Florestas), 2007). Cost levels for 1965 (year taken for the

1960s), 2005 and 2007 can be coupled to cumulative production in Brazil for those years. Based on annual production estimates (see Figure 5-1) cumulative production experienced 4.4 doublings over that period, increasing from 1.4 to 30 EJ (cumulative). An experience curve fitted to these data points results in a progress ratio of 63%. Given data limitations however the uncertainty is considerable. One particular uncertainty follows from the assumption that the obtained cost reductions result exclusively from experience gained in Brazil. Globally, more than 20.1 million hectares were under eucalyptus production in 2009 to which Brazil contributed one-fifth with more than 4.2 million hectares; followed by India at 3.9, China at 2.6 and Australia at 0.9 million hectares; the remaining (> 42%) eucalyptus production took place in other countries across the globe (GIT, 2010). When it is assumed that the Brazilian cost level in the 1960s resulted primarily from developments within Brazil, while over time knowledge spill-over from developments in other countries contributed to Brazilian cost decreases, the slope of the experience curve would be flatter than is suggested by the slope (63%) fitted for the isolated Brazilian case. Following this reasoning, the initial 1.4 EJ is kept constant but cumulative production in 2010 is assumed to be approximately five-fold of the 30 EJ calculated for the Brazilian case only which equals to 143 EJ. With unchanged cost levels this leads to a PR of 73%.

Most important cost reduction in Brazil was realized with improved characteristics through breeding. Significant cost reductions were established through mechanization in harvesting as a result of up-scaling and professionalization. Smaller foresters rely on semi-mechanized systems operating chainsaw harvesting which requires extra manpower. Larger forestry companies (paper and pulp, steel, *etc.*) use highly mechanized methods operating large harvesters that automatically fell, skid, delimb and debark the tree before loading. Transportation costs declined in recent decades due to the outsourcing of transport to specialized companies. As a result vehicle fleets are kept up to date and trucks have increased in size. In addition, these companies cover auxiliary services such as road maintenance, (un)loading, *etc.* (Seixas, 2009). All these improvements together result in more efficient and cheaper transport services.

Italian poplar. Summation of the yearly production figures shown in Figure 5-1 (and extrapolation from 2007 to 2010) indicates an approximate cumulative production of 214 PJ[1] between 1935 and 2010. To estimate yield developments, annual production figures were divided by the yearly area that was felled between 1955 and 1999 (ISTAT (Istituto nazionale di statistica), 2011). Performing linear regression to the derived yields and applying the obtained parameters to the period 1955-99 suggests an approximate tripling of average poplar yields from 4.4 to 13.1 t ha^{-1} y^{-1} over those 44 years. For the current situation, the range was given from extensive management (9 t ha^{-1} y^{-1}) to the current average (14 t ha^{-1} y^{-1}) and state-of-the-art levels (18.5 t ha^{-1} y^{-1}) (Bergante et al., 2006). The data used to quantify past developments in per hectare production costs (at the field level) were based on fourteen studies (Prevosto, 1963; Prevosto, 1965; Prevosto, 1980; Prevosto, 1980; Arru and Prevosto, 1981; Prevosto, 1982; Prevosto and Silvestri, 1982; Prevosto, 1985; Prevosto, 1989; Frison et al., 1990; Borelli et al., 1994; Borelli, 1996; Borelli and Fini, 1999; Coaloa et al., 2005), covering the period 1963 to 2005 (see Appendix B).

[1] A linear production increase was assumed from 0 PJ at the start of production in 1935 to 0.56 PJ in 1950, the first year of recording.

Over that period data indicate a 26% cost decrease. For 2010, average production costs were estimated at 4.5 € GJ^{-1} (see the previous section). To these data an experience curve is fitted, indicating a progress ratio of 74% ± 4% with an R^2 of 0.73, reached over nearly four cumulative doublings, see Figure 5-4.

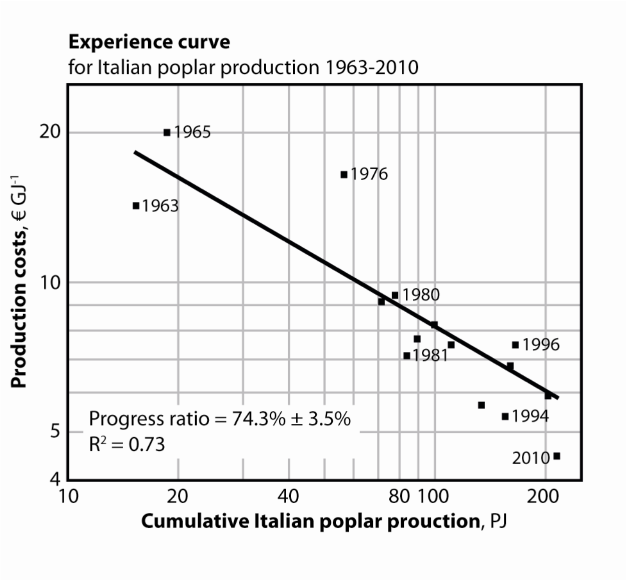


Figure 5-4 Experience curve for Italian poplar production for the period 1963-2010. Based on Italian production statistics (ISTAT (Istituto nazionale di statistica), 2011), areas of poplar felled annually (ISTAT (Istituto nazionale di statistica), 2011), fourteen bottom-up cost studies (Prevosto, 1963; Prevosto, 1965; Prevosto, 1980; Prevosto, 1980; Arru et al., 1981; Prevosto, 1982; Prevosto et al., 1982; Prevosto, 1985; Prevosto, 1989; Frison et al., 1990; Borelli et al., 1994; Borelli, 1996; Borelli et al., 1999; Coaloa et al., 2005) for the period 1963-2005 and three studies (Coaloa et al., 2005; Bergante et al., 2006; Facciotto, 2009) for the state-of-the-costs in 2010. For details see appendix A.

The value for 2010 applies to the state-of-the-art rather than to average values. Consequently, this value is low compared to the fitted curve, especially considering that little additional (cumulative) production was established in recent years. However, when the 2010-value is compared to the data points representing the lowest cost-estimates (e.g. 1963, 1981, 1994) they seem in line with these data points. Next, in general terms, the PR falls within the range of PRs found in literature, for example for annual crops used for biofuels (Berghout, 2008; Hettinga et al., 2009; van den Wall Bake et al., 2009). The correlation and significance of the fit are reasonable. What introduces uncertainty to the outcomes, however, is the limited number of studies that are available prior to 1980, and a data gap of almost a decade from the mid-1960s to mid-1970s. In addition, the four studies that are available prior to 1980 show large variations between subsequent years (1963 and 1965) and relative to the fitted curve (1976). This variation is among others reflected in the R^2 and the associated uncertainty of 3.5%. However, a change of either of these values could have a considerable impact on the slope of the curve. Uncertainties are discussed in more detail in section 5.6.

The single most important factor that brought down costs were yield increases. Bergante *et al.*, 2006 (Bergante et al., 2006) couples yield levels reached in poplar production directly to the management intensity that is applied, distinguishing between low, medium and high intensity management with the corresponding yield levels 9, 11 and 18.5 t ha^{-1} y^{-1} respectively. Based on this, average intensity levels in 1955 at 4.4 t ha^{-1} y^{-1} can be considered low while current average yields of 14 t ha^{-1} y^{-1} can be considered medium to high: and thus leave room for future improvement. Since the start of commercial production in the early 1960s, extensive research has been performed to improve yields by developing clonal varieties, by cross-breeding different species and by experimenting with different spacing configurations (Facciotto and Bergante, 2006). With regard to establishment, maintenance and harvesting operations, ongoing mechanisation has played a key role in reducing labour inputs. An example is the change from manual to fully automated tree planting (see Table 5-3). Another example is the changing harvesting routine: traditional tree harvesting required a laborious harvesting routine of cutting, de-branching and cutting-to-length, for SRC a harvester is used that fells and chips the trees in one pass. While mechanisation and experiments on plant varieties have led to major cost decreases, future opportunities are likely to come from optimising input regimes and ground operations (precision farming).

Swedish willow. With 37 PJ of cumulative production to date, willow production in Sweden has achieved only modest scale. Its production is still regarded as an emerging agricultural activity in Sweden (Rosenqvist et al., 2005). Other countries that have produced willow to some extent include the UK, the US and Poland. The UK had planted 2800 hectares by 2008 (SAC, 2008). Volk *et al.* (Volk et al., 2006) provide a comprehensive overview of developments in willow breeding and hybridization which has led to significant yield increases reported by several sources. Breeding programs in Sweden resulted in variable yield increases depending on site-specific circumstances of 12-67% (Larsson, 1998; Larsson, 2001) and 8-143% in the UK (Lindegaard and Barker, 1997). For example new breeds that are frost-resistant will increase yields more in a region that previously encountered losses due to frost than in a region that had no such problems. Consequently, studies that point out the prospects for cost reductions (see section 5.1) are more abundant than studies that elaborate on past achievements. Mola-Yudego (Mola-Yudego, 2010) estimates an increase of average yields in central Sweden between 1990 and 2005 from 6 to 8 t ha^{-1} y^{-1}. Christersson (Christersson et al., 1994) estimates yields of 6-8 t ha^{-1} y^{-1} when extensively managed and 10-12 t ha^{-1} y^{-1} when intensively managed on commercial scale plantations. Key selection criterion for willow is its frost tolerance rather than its yield (Larsson, 2007). Improvements in harvesting operations in recent years have not led cost reductions of harvesting operations because costs for fuel and labor have increased (Larsson, 2007).

5.4.2 Exploring improvement potential and minimum cost levels

Cost reduction options, the preconditions to achieve those and respective uncertainties are summarized in Table 5-3 and discussed in more detail below. Based on these insights and the cost ranges identified minimum cost levels are derived, shown in Figure 5-5.

Brazilian eucalyptus. Delivered costs for Brazilian eucalyptus are projected to ultimately drop from the current 2.8 € GJ^{-1} to just under two euro's at 1.9 € GJ^{-1}. Future cost decreases can be achieved by yield increases through (breakthrough) innovations in breeding and hybridization, further optimization of silvi-culture operations and efficiency improvements in local transport. Efforts in the development of improved traits in species focus on pest and draught resistance (SUZANO, 2011). In seedling production and plantation setup, costs can be reduced through training of personnel to improve quality, prevent failure during planting and better nursing at the start of growth (Leite et al., 2005). Furthermore, restrictive tillage could save costs (De Oliveira et al., 2009) while at the same time reducing organic matter losses and maintaining soil fertility and structure (Gonçalves et al., 2004). Distinctive to eucalyptus production are the high cost for pest control, in fact the single highest contributor to establishment and maintenance costs. This involves operations to combat insects, mainly ants and termites. Cost can be reduced through the application of pest-resistant breeds and through targeted pest control of local infestations rather than preventive widespread pesticide application. With regard to harvesting, an expansion in the adoption-rates of fully automated harvesting equipment could reduce costs (Techelatka, 2009). Average transport costs can be reduced by better planning, further progress in cutting overhead costs and increasing truck-use efficiencies (Caixeta-Filho, 2003). Couto *et al.* 1995 assessed the cost performance of eucalyptus monocultures versus systems that applied eucalyptus combined with intercropping beans. They conclude that the intercropping system could improve cost performance (overall revenues over the plantation lifetime) with 34-65% per volume of timber harvested (Couto et al., 1995).

Italian poplar. For Italian poplar production, costs could ultimately be reduced from 5.5 to 2.2 € GJ^{-1}. An increase of yields from current average yields (14 t ha^{-1} y^{-1}) to state-of-the-art levels (18.5 t ha^{-1} y^{-1}) could reduce costs most. The augmentation of yields could be established by further improvements through breeding and through optimising, chemical pest treatment, soil management and fertilisation. With regard to soil management, costs can be cut through the planting of a vegetative (grass) cover which prevents the need for manual, mechanical or chemical weeding. In dry areas the latter measure is not feasible because competition for water is too high. A reduction in fertilisation costs and environmental impacts can be achieved by avoiding over-fertilisation; through a lower frequency of fertilisation along a rotation or by adjusting application rates to actual plant needs (balanced fertilisation) (Coaloa et al., 2005).

Swedish willow. Current average willow production costs in Sweden amount to 4.4 € GJ^{-1}. Further developments in raising yields, improved maintenance and technological improvements of harvesting equipment could reduce costs to 1.9 € GJ^{-1}. These figures are at large in line with values reported in literature. For willow, estimates for delivered costs vary from 4.1 € GJ^{-1} in 2005 (Rosenqvist et al., 2005) to a range specified for willow produced in Northern Europe at 3.5-5.3 € GJ^{-1} (Ericsson et al., 2009) and a low estimate at 2.1 € GJ^{-1} (3.0 \$ GJ^{-1}) for the North-western United States (Volk et al., 2006). Cost level in Poland are slightly lower than in Sweden mainly due to lower labour costs (Stolarski et al., 2007). Additional reduction in establishment costs can be reached through adapted fertilization e.g. by applying balanced fertilization and by using low-cost fertilization options for example organic waste such as animal manure, sewage sludge and waste water instead of mineral fertilizer (Weih, 2007). In the first phases of SRC-willow production, harvesting was done by deploying purpose build cutting-heads on conventional harvesters. Problems that occurred were that material was not robust enough leading to fracture and that the flow through harvester and chipper was not optimal which increased harvesting time. Steady optimisation has resolved this and further improvements are expected (Volk, 2011). When improved harvesting equipment is commercially produced in series it is expected that this equipment can be produced at one-fourth of the current costs (Giglera et al., 1999; Larsson, 2007). However, technical and operational improvements made in recent years did not lead to cost decreases due to increased costs for fuel and labor (Larsson, 2007). Transport operations are not expected to have much room for improvement (Sjöström, 2007).

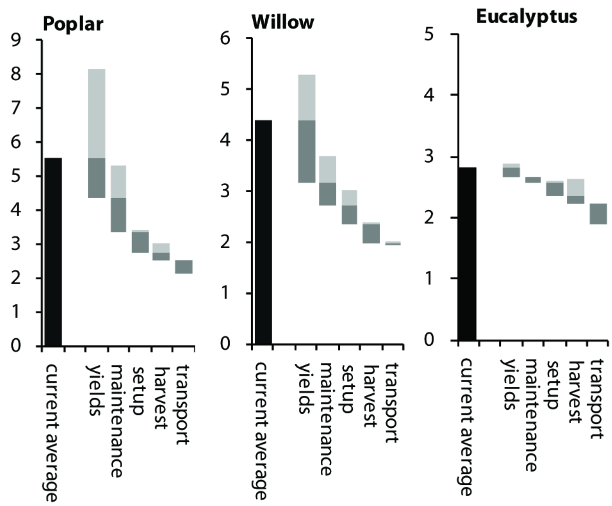


Figure 5-5 Derived minimum cost levels, specifying the improvement potential per step of the production cycle.

Figure 5-5 shows to what extent production costs can be reduced per step in the production cycle and how this affects the minimum cost levels that can ultimately be achieved. Minimum cost levels imply that all improvement options are realized and assuming productive soils are available. Furthermore, it is assumed that the mechanism that causes cost reductions in one production step does not restrict the potential to reduce costs in another production step. This may lead to slight over-estimation of the calculated minimum cost levels.

Table 5-3 Summary of improvement options per step of the production cycle specifying concrete activities and indicating the impact on cost reductions illustrated for three crops willow (W), poplar (P) and eucalyptus (E).

Step of the production cycle	Activity	Impact on costs	
Yields	Yields can be augmented by: implementing improved varieties, raising inputs, increasing input-use efficiencies, optimizing production, *etc.*	High: Higher yields are the single most important factor to reduce production costs. The extent depends on actual yield increases.	n.a.
Seedlings and clones			
Breeding and genetic improvements	Improve crop traits: freeze and draught resistance (Lindegaard et al., 1997; Larsson, 1998; Larsson, 2001; Arborgen, 2011; SUZANO, 2011).	Potentially high: (shift of production frontier) but uncertain both in timing and impact.	Yield increases < 143% (W) [a]
Seedling selection	Prices for seedlings differ depending on species, genetic quality, *etc.*. Selection of the seedling based on cost considerations may result in lower yields thus reducing revenues over the plantation lifetime (Bhati, 1998).	Seedling costs may be related to quality	±39% (E)
Training	Training can improve seedling quality, prevent plant failure during planting and nursing (Leite et al., 2005).	Low to mediate	n.a.
Setup and maintenance			
Pest and weed control	- Change from manual to chemical weeding - Reduce frequency of treatments or quantities applied e.g. by targeting local infestations instead of preventive action.	Low to mediate	-33% (E) -31% (P)
(reduced) tillage	Limited ploughing operations – only the planting line instead of the entire field (De Oliveira et al., 2009).	Low to mediate: May reduce organic matter losses and maintain soil fertility (Gonçalves et al., 2004).	-19% (P)
Fertilization	Timing of fertilization along the production cycle; type of fertilizer used; the amounts supplied to the soil; fertilizer application	Low to high.	-47% (P)
Precision farming	Precision irrigation and nutrient application by implementing tubing close to the rooting system.	Not included in calculations.	n.a.
Rotation management and scale			
Scale of production	purchase of larger volumes may reduce unit prices, e.g. for fertilizers.	medium	n.a.
Rotation optimization	- shorten rotation periods to raise average yields		

	- agro-forestry systems: generating additional (net) revenues from intercropping food crops such as beans (Couto et al., 1995) soy and maize.	Not included in calculation: but potentially high impact	-34 to -65% (E) [b]
Harvest			
Harvesting equipment	(iterative) optimization of harvesting equipment, e.g. from conventional harvesters for common applications to purpose build harvesters to commercialization of	Low to high	-75% (W)
Outsourcing	outsourcing of activities to specialized companies that are outside the expertise of farmers., especially harvesting and transport	Can reduce cost through gaining experience faster and by using capital intensive machinery more efficiently.	
Transport	Increase utilization rates, Scale-up operations, reduce overhead (Faria, 2009). Air-dry harvested stems to reduce moisture content and weight to reduce fuel costs, wearing and toll (Caixeta-Filho, 2003).	Low to mediate	

5.4.3 Application of experience curves to biomass demand projections

In the previous sections, bottom-up cost breakdowns, minimum cost levels for the three crops and top-down progress ratios for eucalyptus and poplar were derived (see Table 5-4). The resulting progress ratios indicate that considerable cost reductions are possible. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The progress ratios found for eucalyptus and poplar fall within the broad range (55–80%) that was found for annual crops. The extent to and rate at which cost reductions can occur within the next 20 years, up to 2030, are evaluated by combining these data with biomass demand projections.

Demand projections such as for primary biomass use worldwide and in Europe suggest that biomass will play a larger role in renewable energy supply. Initially, a large share of the extra demand can be covered by organic wastes, agricultural residues and forest biomass but gradually dedicated production should increase to keep up with demand. Combining the found ranges in progress ratio's to demand projections is a top-down exercise that can illustrate to what extent and at what rates large up-scaling of a global or European SRC industry would reduce costs.

Europe's environmental and biofuel policies (Commission of the European Communities, 2009) have accelerated bioenergy production, which is met by a combination of biomass and biofuel imports and domestic production. Between 2005 and 2010, Europe's total primary energy production from biomass increased by 53%, from 3.0 to 4.6 EJ y-1. This value is expected to grow to 6.2 EJ y-1 by 2020 according to the national renewable action plans (NREAPs) (EurObserv'ER, 2007; EurObserv'ER, 2010). Furthermore, De Wit *et al.* (2010) (De Wit et al., 2010) assessed techno-economical biomass potentials for Europe until 2030 taking sustainability criteria into account. A maximum of 11.0 EJ of perennial woody crops could be produced by 2030, produced on 66 million hectares of cropland (assumed to become gradually available through agricultural intensification). In an optimistic scenario, it is assumed that production will follow an exponential function to increase from current production volumes to 11 EJ in 2030 to account for a gradual increasing production as is described for early phases of the S-shaped diffusion curve. In reality, it is more likely that a crop mix of sugar, starch, oil and herbaceous grassy crops will be produced. In such a more moderate scenario, perennial SRC crop production is assumed to only reach 2.2 EJ in 2030 (one-fifth of the optimistic scenario).

Table 5-4 Summary of the production costs, cumulative produced quantities until 2010 and the progress ratios for poplar and eucalyptus.

	Production costs 2010	**Minimum cost levels**	**Cumulative production until 2010**	**PRs**
	€ GJ^{-1}	*€ GJ^{-1}*	*EJ*	*%*
European SRC production			*0.251*	
Willow	4.4	1.9	0.037	-
Poplar	5.5	2.2	0.214	70.8 -77.8
Eucalypt in Brazil				
National case	2.8	1.9	30 *(Brazil)*	62.6 *(national)*
Global case	2.8	1.9	143 *(World)*	73.4 *(global)*

NB – Numbers are rounded in the table. Calculations were based on the actual figures.

In 2008, global primary biomass production was 50 EJ of which 12.4 EJ consisted of modern biomass, largely residues, wastes, forest biomass and agricultural crops for biofuels. The IPCC projects values for the primary biomass energy supply to increase from those 50 EJ to 80 (75-85) EJ in 2030 and 138 (120-155) EJ in 2050. In addition to these median figures, upper estimates of 150 EJ in 2030 and 300 EJ in 2050 are given for global biomass demand (IPCC, 2011). To estimate the upper limit of the production that could come from SRC production by 2030 we assume that roughly one-fourth[2] of that 150 EJ consists of SRC, about 38 EJ. Using the median IPCC value for primary biomass production by 2030 of 80 EJ and applying the one-fourth share of dedicated cropping systems results in 20 EJ.

[2] To derive an estimate for the SRC production as a share of global primary biomass production by 2030 a study by Dornburg *et al.* (Dornburg V, Van Vuuren D, Van De Ven G, Langeveld H, Meeusen M, Banse M, Van Oorschot M, Ros J, Van Den Born G, Aiking H, Londo M, Mozaffarian H, Verweij P, Lysen E, Faaij A. 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 3(3): 258-267. is used. They define four main categories of biomass feedstocks and attach numbers to their technical potential in 2050. Organic wastes, forestry and agricultural residues represent ~110 EJ. Biomass produced by perennial cropping systems on better lands adds ~120 EJ y^{-1}. Production on degraded and marginal lands could add another ~70 EJ. Surplus forest growth represents ~100 EJ y^{-1} . These numbers provide an indication on how IPCC projections are broken down by 205. The summed total amounts ~500 EJ y^{-1} thus perennial cropping systems contribute roughly one-fourth.

Table 5-5 Application of progress ratios to projections of the (cumulative) production of energy crops globally and in Europe and its effect on future production costs.

	Cumulative production until 2010	Projected demand by 2030[a]	Cumulative demand projection until 2030 [b]	Doublings in production until 2030 [c]	Timing of minimum cost levels reached [d]
	EJ	*EJ*	*EJ*	*#*	*years*
European case					
High case	0.251	11.0	34	7.1	
Poplar					2022-24
willow					2022-24
Low case	0.251	2.2	8.5	5.1	
Poplar					2025-27
Willow					2024-26
Global case					
High case	143	38 [e]	788	1.9	2021-25
Low case	30	20 [e]	509	1.4	2024-30

A – The projected biomass demand quantities by 2030 are discussed in the text.
B – The cumulative demand projection until 2030 uses cumulative 2010 production levels and assumes an exponential increase to 2030 for the European cases (as developments are in the early stages of the S-shaped diffusion curve), whereas a linear increase is assumed for the global cases (as their development is presumed to be in the linear middle-part of the diffusion curve).
C – The number of times the cumulative production volume double between 2010 and 2030.
D – The timing of the moment when the minimum cost levels are reached are based on the initial cost levels in 2010. The progress ratios (either the lower or higher estimate) and the number of doublings reached.

The analysis suggests that at the assumed growth rates for biomass, minimum cost levels could be reached between one and two decades. For eucalyptus production, considering its already substantial production thus far, absolute cost reductions are reached at a slower pace. Assuming global deployment of eucalyptus based SRC, minimum cost levels could be reached between 2021-25. If production (and thus learning) is restricted to Brazil, minimum cost levels are reached between 2024-30.

However, given the modest European production so far, rapid doublings of cumulative production could be achieved, which would allow in principle for rapid learning and cost reductions. Assuming a gradual (but ultimately significant) transition to the large-scale production of willow and poplar (with would require dedicated policy support), minimum cost levels could in theory be reached between 2022-27, roughly equalling the Brazilian production costs. Such a scenario is not impossible, but should be treated with caution: the policy measures to achieve such growth would need to be substantial and require significant up-front learning investment, which is unlikely to happen. Also, SRC systems are perennial, so typically 2-5 years are needed to pass on gained experience and apply it to a next generation. Nevertheless, similar cost reduction *have* already been achieved in the past, e.g. for traditional eucalyptus production in Brazil or corn production in the US. To achieve such cost reductions, simultaneous dedicated private and public R&D efforts would probably be needed, similar to for example the past Brazilian development of eucalyptus (and sugarcane for that matter). In addition, it can be argued that, given the similarities of (the improvement potentials of) steps in the production cycle (see Table 5-3), global SRC systems may over time develop into a single global learning system which, from the insights gained in this analysis, causes more rapid learning and consequent cost reductions.

5.5 Conclusions and discussion

The present paper gives an overview of past developments, the current status and an outlook of costs and yield developments in dedicated wood production systems for energy use for poplar, willow and eucalyptus. A main objective was to evaluate the extent to which experience curves could be applied to perennial wood production systems. To evaluate the future cost reduction potential for dedicated wood cropping systems, bottom-up insights and top-down approaches (including experience curves) were combined and applied to global and European demand projections to sketch scenarios for future deployment of SRC systems and possible developments in production costs.

Current average production cost levels are highest for poplar (5.5 € GJ^{-1}), followed by willow (4.4 € GJ^{-1}) and eucalyptus (2.8 € GJ^{-1}). Based on the cost reduction options minimum cost levels are derived for all crops around 2 € GJ^{-1}.

Past cost developments indicate that per hectare cultivation costs have decreased by roughly two-thirds in recent decades for poplar in Italy and eucalyptus in Brazil. For Sweden, due to the limited volumes produced, no overall cost decline was observed over the two decades that willow is produced. In all cases significant variations in yield levels are observed that depend on site specific soil and climate conditions and the intensity level of the cultivation. Yield increases have been the most important driving force behind production cost declines. Yields were augmented through implementation of improved breeds and clonal varieties, increased fertilisation levels, better pest control and ongoing mechanisation in planting and tillage. Further progress, outside the cropping system, was reached in harvesting and local transport. In harvesting, ongoing mechanisation and improvements that were made to harvesting equipment were the most important aspects. In transport, improved road networks, increasing truck-size and truck reliability and improving use-efficiencies have brought down costs. An option not quantitatively considered in the present study but with the potential to improve overall plantation revenues considerably is the application of agro-forestry systems (Couto et al., 1995).

It has proven difficult to derive empirical progress ratios for the assessed cases due to limitations and heterogeneity of data, although the extent and type of these limitations varied per case. Poplar production in Italy presents the best case that was assessed in the present study due to the availability of bottom-up cost overviews for consecutive years. Variation in the cost data with regard to steps of the production cycle included, rotation periods and plantations lifetimes considered required data adjustments to compare data. For Brazil limited cost data were available. To derive progress ratios the cumulative produced volumes were varied, applying cost levels to Brazilian and global production.

Given data limitations, the derived progress ratios should be considered as first order estimates. The resulting progress ratios indicate that considerable cost reductions are possible. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in

Italy (71–78%). The progress ratios found for eucalyptus and poplar fall within the broad range (55–80%) that was already found for annual crops. On average, it appears that PRs for the production of annual and perennial crops seem to be on the low side, i.e. cost reduction occurs faster compared to other energy supply technologies that display a mean progress ratio of 84% (Junginger et al., 2010). On the other hand, because exogenous factors such as cost for labour, land, fertilizer and diesel play a major role in the total production costs and depend on market developments they are not subject to learning as such. In addition, the fact that future yield increases may be more difficult to achieve over time could result in lower cost reductions and eventually in reaching minimum cost levels. However, for the next 10-20 years outcomes suggest that, on average, significant reductions are possible.

The fact that future cost projections do not explicitly consider variations in exogenous cost factors, unrelated to technological progress (such as prices for land, labour and inputs), introduces additional uncertainty in the outcomes. Prices paid for diesel and nitrogen fertilizers are influenced by fossil fuel prices. Considerable volatility and current high price levels show the variability of these inputs and their impact on the prices of manufactured goods. The (opportunity) costs of land depend on (local) scarcity. As a result of an increased demand for biomass feedstock's, on top of rising food demand, the demand for agricultural land may rise this can lead to higher land prices (Banse, 2007). Labour costs, although in general not very volatile, generally rise as economic development continues. To illustrate the labour cost differences: wage levels were about one-tenth in Brazil of what they were in Sweden in 2000 (LABORSTA, 2011).This usually leads to deployment of more capital reducing the role of labour.

The crucial role of stimulating policies for the establishment and growth of production volumes and subsequent cost reductions has been apparent in all three cases. In Brazil two national programs have increased eucalyptus production greatly, a reforestation program focussed on securing forest supplies while another aimed at substituting imported fossil fuels by forest products. In Sweden, in the 1980s research grants led to the development of improved varieties such as frost resistant species which boosted yields. For poplar in Italy, government intervention had been modest. However, a financial aid scheme to financially assist farmers had actually increased production figures until it was abolished because it appeared conflicting with EU policy. Nevertheless, the possible influence of exchange of experience and learning beyond national borders remains unclear and requires more in-depth analysis.

The scenario outcomes suggest that when European biomass ambitions are increasingly met by European SRC production, learning induced cost reductions could be achieved fairly rapidly, and minimum cost levels of around 2 € GJ^{-1} could be reached for poplar and willow between 2022-2027 for better quality land. For eucalyptus production, considering its substantial production thus far, absolute cost reductions are reached at a somewhat slower pace. At fast global deployment of eucalyptus based SRC, minimum cost levels of also 2 € GJ^{-1} could be reached between 2021-25. When learning is restricted to Brazil, minimum cost levels would be reached between 2024-30 but this is a hypothetical case. This analysis suggest that in principle, the EU might produce lignocellulose at cost-competitive levels within the next 15-20 years, However, both progress ratios and production projections remain uncertain. Realizing such deployment and cost reduction would also require a EU-wide dedicated policy effort and large up-front learning investments. Nevertheless, the findings warrant further research into experience curves for perennial crops. The paper points out methodological issues regarding the lack of data, difficulties of comparing various crop types and production systems and the importance of geographical system boundaries. Further investigation could focus on the production of (in particular) eucalyptus in other countries than Brazil, advances in other lignocelluloses crops, but also more annual crops to get a better (and more quantitative) overall understanding of future learning potential of various crop types. Next, a component experience curve (Ferioli et al., 2009; Yu et al., 2011) could be applied to evaluate more in-depth which steps in the cropping system have contributed and can contribute to deliver cost reductions in the future. Furthermore, the found progress ratio's for SRC systems could be deployed in energy scenario modelling, e.g. to assess the effect of policy interventions on the rate at which cost reduction are reached, also in relation to competing production systems such as between power generation and biofuels.

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Appendix A – Italian poplar production.

The breakdown of poplar production costs per hectare over time presented in (Appendix A Figure 5-6) shows large variation in cost levels. Large cost variations from one year to the next (e.g. 1980-81 or 1994-95) suggest differences in methods used, steps of the production cycle included or other differences in the approaches applied. A linear regression trend line was fitted to the fourteen data points showing an average reduction of total costs of -26%, from 23.4 to 13.8 k€ ha^{-1}, between 1963 and 2005. As is clear from the graphic the variation between values is high which is reflected in a poor R^2-score of 0.27. Further scrutiny of the relative contributions to overall cost reductions reveal the largest decline in setup costs (-61%), followed by maintenance (-16%) and other costs (-1%). The initial increase in maintenance costs can be related to increasing use of fertilisers and other inputs in a time when plantations professionalised also reflected in progressively higher yields that were established (see Figure 5-6).

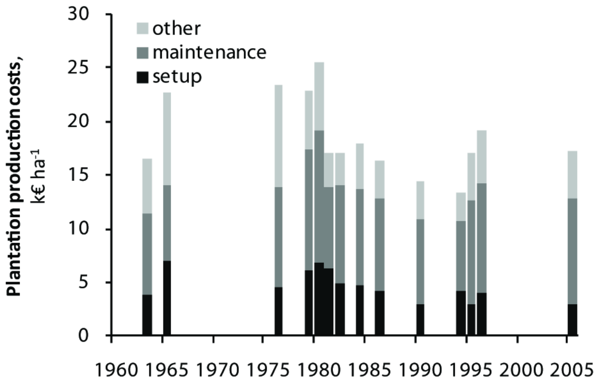

Figure 5-6 Breakdown of Italian poplar production costs per hectare for a typical plantation lifetime of 10 years; displayed are fourteen bottom-up cost studies (Prevosto, 1963; Prevosto, 1965; Prevosto, 1980; Prevosto, 1980; Arru et al., 1981; Prevosto, 1982; Prevosto et al., 1982; Prevosto, 1985; Prevosto, 1989; Frison et al., 1990; Borelli et al., 1994; Borelli, 1996; Borelli et al., 1999; Coaloa et al., 2005), executed between 1963 and 2005.

Data adjustments. Some adjustments had to be performed to the data to make them better comparable. In the 1994 study (Borelli et al., 1994) no costs for irrigation were considered in contrast to the other studies. As an estimate for irrigation costs in 1994, the average costs were taken from 1990 (Frison et al., 1990) and 1995 (Borelli, 1996). The study for 1965 (Prevosto, 1965) considered a plantation lifetime of 15 years compared to the other studies that considered a 10 year lifetime. While this did not affect the cost for the plantation setup, the costs for maintenance and other cost were adjusted for this difference. The 1990 study did not consider fiscal costs and some costs for maintenance; these were taken from the 1986 study. Furthermore this study assumed a 6-year plantation lifetime for which maintenance costs were adjusted to make it comparable to the general 10-year plantation lifetime.

6 Competition between biofuels: Modelling technological learning and cost reductions over time

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ABSTRACT A key aspect in modeling the (future) competition between biofuels is the way in which production cost developments are computed. The objective of this chapter is threefold: (1) to construct a (endogenous) relation between cost development and cumulative production (2) to implement technological learning based on both engineering study insights and an experience curve approach, and (3) to investigate the impact of different technological learning assumptions on the market diffusion patterns of different biofuels. The analysis was executed with the European biofuel model BioTrans, which computes the least cost biofuel route. The model meets an increasing demand, reaching a 25% share of biofuels of the overall European transport fuel demand by 2030. Results show that 1st generation biodiesel is the most cost competitive fuel, dominating the early market. With increasing demand, modestly productive oilseed crops become more expensive rapidly, providing opportunities for advanced biofuels to enter the market. While biodiesel supply typically remains steady until 2030, almost all additional yearly demand is delivered by advanced biofuels, supplying up to 60% of the market by 2030. Sensitivity analysis shows that (1) overall increasing investment costs favour biodiesel production, (2) separate gasoline and diesel subtargets may diversify feedstock production and technology implementation, thus limiting the risk of failure and preventing lock-in and (3) the moment of an advanced technology's commercial market introduction determines, to a large degree, its future chances for increasing market share.

6.1 Introduction

Driven by general sustainable energy targets and specific biofuel targets to curb green house gas (GHG) emissions, concerns regarding security of supply and especially in recent years rising oil prices, the production and use of biofuels have been steadily increasing globally in the last decades. The EU encourages developments to achieve an ambitious 10% share of biofuels by 2020 (Commission of the European Communities, 2009). Driven by this target the demand for biofuels in Europe can be expected to face a strong increase compared to the current (2007) 2.6% (EurObserv'ER, 2008). With such turbulent short-term development comes the need for an integrated long-term vision for biofuels, as set in the REFUEL project (Londo et al., 2010). Amongst other aspects, the role of technological learning (and associated cost reductions) is a crucial factor affecting the possible market diffusion of various 1st and 2nd generation biofuels.

Given the complex interactions between the various biofuels and fossil transportation fuels, the use of models for biofuel market penetration can be a useful tool for policy makers, market actors and scientists. The use of energy models is not new – a wide variety of energy models have been constructed to provide policy makers with a better insight into the complexities of energy system development under various policy objectives. Many describe the complete energy system either with a technical 'bottom-up' (systems engineering) approach or with a macro-economic 'top-down' approach (Junginger et al., 2008). Specifically regarding the market penetration of biofuels, a limited number of models exist, e.g. the ESIM and LEITAP models (Banse, 2007), the BioTrans model (Lensink et al., 2010) (used in this study) for Europe or the biodiesel model (Bantz and Deaton, 2006) for the US.

A crucial aspect of these models is how technological learning and subsequent cost reductions over time are taken into account, as these can drastically change the economic competitiveness and thus market share of a biofuel compared to other (fossil and renewable) fuels. Some energy models tend to define future cost levels ex ante, i.e. cost reductions are independent of market developments. This approach ignores demand driven market dynamics and the notion that technological learning (and subsequent cost reductions) depend on the degree to which a technology is utilized; a phenomenon which has been observed numerous times, and that can be quantified using the experience curve approach. For this reason, endogenous learning has increasingly been incorporated in many energy models but this has not been attempted for models specifically focusing on biofuels for transport.

Analysis for this study is executed with the BioTrans model, which assesses the European biofuel mix that establishes given a target-driven biofuel demand. The model fills-in the yearly demand by computing the least cost biofuel mix. The development of production cost can be modeled endogenously which makes BioTrans particularly suitable to assess the influence of specific learning parameter values on competition between fuels over time.

The objective of this study is threefold, it aims to
(1) Construct the (endogenous) relation between cumulative installed capacity and associated production cost reductions, or if this is not possible construct an (exogenous) relation following a hybrid approach, in which insights from engineering studies (mainly regarding scale effects) are combined with a scale-independent experience curve approach for both 1st and 2nd generation feedstocks and 1st and 2nd generation biomass-to-biofuel conversion technologies,
(2) implement these relations in the BioTrans model and
(3) illustrate the consequences of these assumptions on the rate of technological learning, its effect on market diffusion and determine the future biofuel mix as a result of the market competition.

6.2 Methodology

6.2.1 Technological learning and cost reductions in feedstock production

Feedstock production costs can reduce over time, mainly by gaining experience with its production. The lack of historical production cost data prohibits the possibility to model cost developments endogenously. In principle, however, feedstock production costs can be modeled endogenously, i.e. relating annual production volumes (as a proxy for gained experience) to decreasing production costs. Analyses performed for sugarcane in Brazil (van den Wall Bake et al., 2009), for corn in the US (Hettinga, 2007) and for rapeseed in Germany (Berghout, 2008) demonstrated that indeed cost reductions of (food) crops do follow an experience curve pattern. Unfortunately, for all (other) crops considered in the study, no such studies are available which could provide the necessary time series and trend lines. However, the studies mentioned show that an increase in productivity is the single-most important driver for decreasing production costs for feedstocks, contributing between 65–85% to total cost decline, therefore making it a suitable parameter for estimating future cost reduction potentials. Increased productivity is an important measure for cost reduction as it shows the results of improving management (e.g. adequate pest control, optimized fertilizer application etc.). Another aspect contributing to reducing costs is economies of scale in transportation, e.g. the use of larger trucks, trains or ships (van den Wall Bake et al., 2009).

The productivity increase of agricultural commodity crops was modeled on the basis of a fixed annual increase, with the annual increment being developed from a time series analysis of the specific crop (Ewert et al., 2005). Despite there being a physical limit to this approach over a long duration, this trend is amply confirmed for Europe over the last four decades (Evans et al., 1997; Calderini and Slafer, 1998). An equation:

$$Y_e = f_y\, t_y + b \tag{6.1}$$

was fitted to the historical data. The relative yield improvement (% y^{-1}) decreases over time as shown in Figure 6-1. We have equated yield improvement rate to be the same as the production cost decrease during the period of our analysis from 2005 -2030 with the initial crop production costs taken from (De Wit and Faaij, 2009). Lignocellulosic crop productivity development curves are generally unavailable except for some experimental tree crops such as Poplar, Willow and Eucalyptus (Campinhos, 1999; Mercer and Underwood, 2002) and herbaceous species such as Miscanthus and Switchgrass (Mola-Yudego and Aronsson, ; Van Hulst, 2008). Instead of fitting a curve to empirical data, literature data (Wyman, 1999; Rosenqvist et al., 2005) have been used to project the maximum productivity (and thus cost reductions) for 2030.

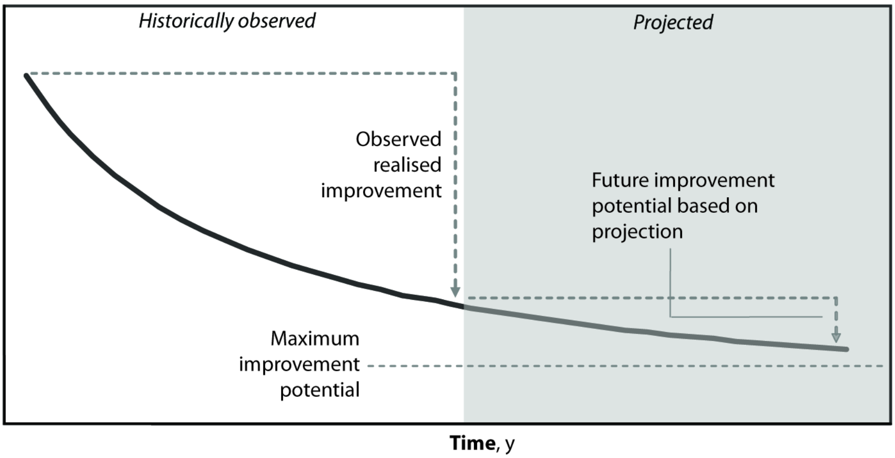


Figure 6-1 Production costs improvement potential over time.

6.2.2 *Technological learning and cost reductions for conversion technologies*

An experience (or learning) curve, as this empirical causality relation is often referred to, expresses the cost decline by a constant factor with each doubling of cumulative number of units (or capacity) produced or installed (Boston Consultancy Group (BCG), 1968). This relation can be written as:

$$Cost_{cum} = Cost_o\,(Prod_{cum})^b \tag{6.2}$$

$$PR = 2^b \tag{6.3}$$

Future production costs ($Cost_{cum}$) can be projected with the experience curve (equation 3) if the costs ($Cost_0$) are known at the start of production and the cumulative (unit) production ($production_{cum}$) at a future moment in time. The progress ratio (PR) is a parameter that can be derived from the experience index (equation 4), that expresses the rate at which costs decline for every doubling of cumulative production. For example, a progress ratio of 80% equals a 20% cost decrease for each doubling of the cumulative capacity. Production cost decrease over time due to improvements in the process (incremental innovations), scaling up of individual units, experience gained by operation and maintenance *etc*. (Junginger et al., 2006). The use of experience curves for estimation of the progress ratio is often used for analysis of (historic) cost data coupled to (cumulative) production figures. Based on production cost developments over cumulative production, progress ratios have been derived for a multitude of energy technologies, including biomass combustion and biomass anaerobic digestion technologies (Junginger et al., 2006) and 1st generation biofuel conversion technologies (Hettinga, 2007; Berghout, 2008; van den Wall Bake et al., 2009). A meta-overview of these data and progress ratios, based on (bottom-up) studies, is presented in section 3.2. These data are applied in the BioTrans model to endogenously model cost development of 1st generation conversion as a function of cumulative produced biofuels.

However, for 2nd generation biofuel plants, the problem of data availability arises. Currently, only experimental-scale and pilot plants for both FT and LE production exist. First commercial units are expected to go online in the next few years (Choren, 2007; USDOE, 2007). Consequently, it is not possible to empirically determine progress ratios for 2nd generation biofuel conversion technologies. A solution to this could be to take a 'best guess' progress ratio. But as the progress ratio is often one of the most sensitive parameters for model outcomes, this was not deemed an option. A more refined possibility would be to estimate progress ratios for separate component of a biofuel plant, as done earlier for example for Biomass Integrated Gasification Combined Cycle plants (Faaij et al., 1998; Uyterlinde et al., 2007). Still, this method relies on expert judgments to estimate progress ratios. Therefore, for this study, a hybrid approach was developed, in which insights from engineering studies (mainly regarding scale effects) were combined with a scale-independent experience curve approach. Both are described in more detail below.

Scale-dependant learning. A widely applied concept in engineering studies is the use of scaling laws. The scale learning approach describes a relation between increases in plant scale and associated decreasing production costs, according to a scale law (Haldi and Whitcomb, 1967; Blok, 2006) which can be written as:

$$Cost_{P2}/Cost_{P1}=(Scale_{P2}/Scale_{P1})^{R} \quad (6.4)$$

The capital cost for a process configuration $Cost_{P2}$ is determined by the current cost of the installation $Cost_{P1}$ and by the ratio of the future scale and the current scale to the magnitude of the scale factor R, following equation 4. Future cost can be estimated by applying an empirical determined or theoretically derived scale factor. Typically, empirically determined scale factors vary between 0.6 – 0.9. Note that for many plant components maximum sizes exist, which dampen or even stall the reduction of costs with increasing scales. Also, for (biomass) plants, larger plant sizes require larger amounts of feedstock, typically increasing average feedstock costs. Thus, conversion plants have an optimum scale at which specific fuel production costs are minimal (Nguyen and Prince, 1996).

As engineering studies have been published for 2nd generation biofuels which specify the (expected) scale effects, it is possible to integrate the scale effect into BioTrans. To incorporate scaling in the model, three boundary conditions had to be included:
(i) First, there is a maximum speed with which technologies can be scaled-up. This is primarily related to technological learning – larger plants often display new problems, which have to be solved before further scaling can take place. Another requirement is a growing market, which allows producers to increase production by building a bigger plant (or by operating facilities, with a similar or smaller scale, in series). This phenomenon has been observed for many energy technologies (Grübler, 1998) e.g. natural gas turbines

(Watson, 1997), wind turbines (Junginger et al., 2005) and fluidized bed boilers (Koornneef et al., 2007). Typical doubling times for these technologies are 3 – 5 years.
(ii) Second, as argued above, an absolute maximum plant size is postulated.
(iii) Third, a restriction is introduced that a single plant cannot supply more biofuels than a fixed percentage of the total market capacity (e.g. 5%) at any given moment. This restriction is necessary to prevent that in the model runs, a single plant could supply unrealistic high shares of the market. These limitations can be modeled using equation 5.

$$Scale_t = Scale_o \text{ e EXP } [\{ LN(2)/doublingtime \} t] \quad (6.5)$$

with $Scale_t \leq Scale_{MAX}$ and $Scale_t \leq x\% \cdot MarketCapacity$

Figure 6-2 illustrates the consequences of these limitations, following the line segments indicated with letter symbols. Section A-B is the potential scale-up until limited by the maximum market-share supplied by a single plant. Section B-C is the assumed market growth rate with the plant scale following 5% of the market share. The plateau, from C-D, represents the physical limiting scale for the plant considered. At slower up-scaling (2x and 4x) it is more likely that the physical limit limits plant scale rather than the growth rate of the market.

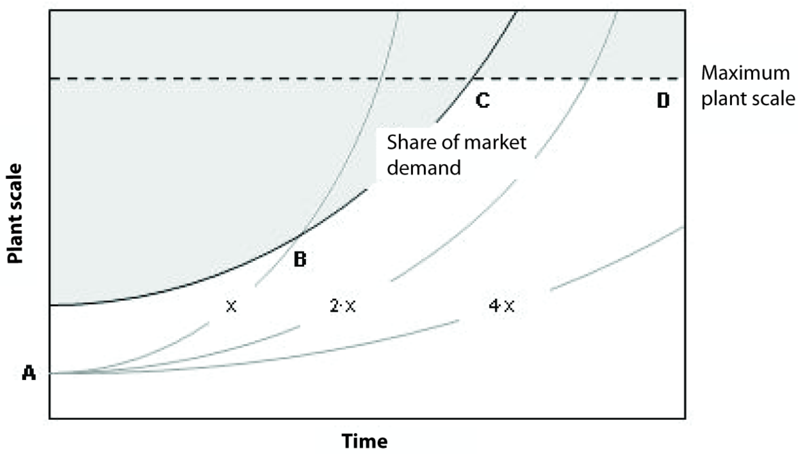


Figure 6-2 Schematic overview of the doubling-time approach with two restrictions (maximum scale and maximum market share).

Scale-independent learning. In addition to scale-dependant cost projections, additional reductions can occur through technological process improvements which are not related to scale. Examples are increased efficiency, life time prolongation of catalysts, the use of advanced materials etc.. Scale independent learning has reduced the costs of ethanol production from corn (Hettinga, 2007), and sugar cane (Hamelinck et al., 2005; van den Wall Bake et al., 2009) by 25-50%. These scale-independent cost reductions where related to the cumulative volumes of ethanol produced. Thus it was possible to derive experience curves (and PRs) for scale-independent learning. Due to the lack of any more adequate data, the PR-ranges of the 1st generation biofuels technologies were used in Biotrans to model scale-independent cost reductions of the 2nd generation technologies.

6.3 Data input

6.3.1 The BioTrans model

The BioTrans model is utilized for optimizing full supply chain allocation. In the fuel supply chain, BioTrans considers four steps (1) feedstock production, (2) biomass-to-biofuel conversion, (3) fuel distribution and (4) end-use. The transport costs are dependent on transport distance, the distribution of fuels and expenses for end use are considered fixed and only fuel dependant (Lensink et al., 2010). Due to lower average density and hygroscopic characteristics additional costs for bioethanol and biodiesel compared to fossil equivalent fuels are respectively 0.88 and 0.12 € GJ^{-1}.The cost for feedstock production and the conversion of feedstocks to fuel change over time, as a result of cumulative produced volumes. The model essentially aims at finding the minimal cost allocations along the supply chain given projections of demand (e.g. based on biofuel policy targets), potentials and technological progress. Between the different steps in the supply chain, trade is possible between member states. The model uses as input a wide range of (mainly techno-economic) parameters regarding the current European biofuel situation, as well as macro-economic and technological projections. The output of the BioTrans model includes detailed allocations of production, processing, transport and distribution of energy crops and biofuels.

Biotrans can model 1st-generation fuels (biodiesel based on vegetable oil crops and used fats, and ethanol based on sugar- and starch crops) and a number of 2nd generation fuels: Fischer-Tropsch diesel (FT) and DiMethylEther (DME) through gasification, substitute natural gas (SNG) through either gasification & methanation or anaerobic digestion and lignocellulose ethanol (LE) through fermentation. Note that, at least for the European situation 1st generation biofuels are generally produced from expensive feedstocks in established and optimized technologies, while the 2nd generation is expected to use relatively lower cost feedstocks and what are presently capital intensive multistep process technologies.

The synthesis paper in this volume (Londo et al., 2010) develops three biofuel target scenarios. Of the three developed scenarios the high target scenario is used in this study. The demand for biofuels as a share of overall transport fuels develops as follows: 5.75% by 2010, 14% by 2020, and 25% by 2030.

6.3.2 Feedstock production cost development

Oil, starch and sugar crops. Time series data on the productivity development of crops are used for the period 1961 - 2005 (FAO, 2006). The data are available for country level aggregates, taken for 30 European countries (EU27, Norway, Switzerland and Ukraine). Crops included in this study are rapeseed, sunflower (seed), sugar beet, wheat, rye and corn. For this analysis, developments are described on a national level and for the larger regions of the Western European Countries (WEC) and the Central and Eastern European Countries (CEEC). Rationale for the division between WEC and CEEC is that developments in the agricultural sectors between these two regions have been significantly different, while developments within these regions have been relatively comparable. The WEC have for the last decades made great progress in increasing its agricultural productivity by modernization and up-scaling. Much of these developments have been made possible by an EU focus on and funding for the agriculture sector. The CEEC have dominantly been under centrally planned agricultural policy which initially did raise agricultural output. In the transition to market economies around the 1990s, however, production fell sharply. Distinct differences in these developments have led to considerable differences to the current day with respect to cost levels, mainly for land and labour, affecting crop production costs.

Table 6-1 Yield improvements and production costs for the period 2005–2030 for five crop groups.

Crop group/type	Region	Productivity			Production cost	
		Estimated Yield 2004 [d]	Projected Yield 2030 [e]	Improvement 2004-2030	Production costs 2005 [c]	Production costs 2030
		Tonne ha^{-1} y^{-1}		%	€ GJ^{-1}	
Annual first generation crops [a]						
Oil crops						
Rapeseed	WEC	2,6	3,0	14,6	10,30	8,80
	CEEC	1,9	2,2	16,4	5,53	4,62
Sunflower	WEC	1,9	2,2	14,9	10,30	8,77
	CEEC	1,9	2,4	19,1	5,53	4,47
Starch crops						
Wheat	WEC	5,9	7,9	25,7	9,05	6,72
	CEEC	3,9	4,9	20,4	5,27	4,19
Corn	WEC	9,0	12,8	30,3	9,05	6,31
	CEEC	5,6	7,2	22,9	5,27	4,06
Sugar crops						
Sugar beet	WEC	5,8	7,3	20,7	5,32	4,22
	CEEC	3,3	3,7	12,3	3,66	3,21
Perenial second generation crops [b]						
Lignocellulose crops	WEC	8	13	20 - 35	3,38	2,45
	CEEC	8	13	20 - 35	1,66	1,20
Herbaceous lignocellulose crops[f]	WEC	10 - 20	10 - 20	20 - 35	4,46	3,23
	CEEC	10 - 20	10 - 20	20 - 35	2,74	1,99

A – based on time series data FAOSTAT

B – based on (Smeets et al., ; Ledin, 1996; Szczukowski, 2004; Gumeniuk, 2005; Rosenqvist et al., 2005; Van Hulst, 2008)

C – based on calculations by De Wit and Faaij (2008). Production costs are indicated for crop group averages.

D – the yield level for 2004 is the calculated yield based on the estimated yield development function obtained by linear fitting the historic yield data for the period 1961 – 2004. For many countries time series data were incomplete for the assessed 1961 – 2004 period.

E – the yield level for 2030 is the result of extrapolation of the yield estimated function fitted for historic observed yields for the 1961 – 2004 period as described under d.

F – 2004 yield level estimations for Miscanthus and Switchgrass in oven dry tonnes (odt ha-1 y-1) based on (Smeets et al., 2008).

(Herbaceous) lignocellulose crops. Production costs to date have been relatively high, mostly because their production is geographically spread-out and typically small-scale. Estimates on the potential to reduce production costs for (herbaceous) lignocellulose crops vary from 9% on average for Switchgrass (Smeets et al.), 19% for willow in Sweden (Wyman, 1999) and 35% on average for lignocellulose crops (Rosenqvist et al., 2005). All references state preconditions that have to be met in order to reach the estimated cost reductions, such as up scaling of production, improved and extended machinery use, breeding optimization, improved management through more adequate crop-specific knowledge. Barriers are formed by the limited size of farms, geographical fragmentation etc. (Rosenqvist et al., 2005). Furthermore, the production costs for the base year (2005) are taken from results presented in chapter 2 (De Wit et al., 2010).

6.3.3 Biomass-to-biofuel conversion cost development

All data presented are in 2004 euros. Where necessary data provided in different currencies (e.g. US$) have been converted to euros using the average exchange rate in the year of the publication of the data source. No attempt was made to correct for inflation for the period 2000-2004.

Vegetable oil to bio-diesel. Three process steps are considered to produce biodiesel (1) oil extraction, (2) transesterification of virgin oils from oil seeds – for the two-step process of biodiesel production – and (3) transesterification of used oils and fats for biodiesel production from residue streams. Pure vegetable oil is produced from oil seeds (e.g. rape seed or sunflower) by mechanical pressing or solvent extraction. Used fats and oils can be obtained e.g. from slaughterhouse waste and frying and cooking oil. Biodiesel can, subsequently, be produced from either the obtained pure vegetable oil or used fats and oils by a transesterification process. This technology is long since used and is applied specifically for biodiesel production in Europe (most notably in Germany) since the early 1990s. Data on investment and operation costs are based on various sources (Schöpe and Britschkat, 2002; Körbitz et al., 2004), see Table 6-2. For the estimation of the technological learning, the transesterification process for biodiesel from oil crops and from used fats and oils were taken as one entity. For both technologies typical (large) scale installations (Table 6-2) were considered following (Berghout, 2008). An endogenous learning progress ratio for biodiesel production from pure vegetable oil is estimated in the range of 90% (Table 6-3). The cumulative production volume of biodiesel in the EU25, up to and including 2004, is compiled from data available for the EU15 from 1993 and for the CEEC from 2002 (EUobserver, 2006).

Sugar and starch to ethanol. Production of ethanol from sugar and starch comprises of two major process steps (1) the production of sugar and (2) the fermentation of sugar to ethanol. Production of sugar from sugar crops (e.g. sugar beet) involves crushing, and extraction of the sugar. Production of sugar from starch crops (e.g. wheat) involves milling of the grains to obtain the starchy material, dilution and heating to dissolve the starch and conversion of the starch to sugars by hydrolysis. The data for investment and operation costs (Table 6-2) for conventional bioethanol production, from sugar and starch crops, is based on various sources, but mainly (Lichts, 2004; Mortimer et al., 2004).

Table 6-2 Techno-economic overview for all biomass-to-biofuel technologies considered.

Technology [a]	unit	Amount
First generation		
Oil extraction		
Scale	$kT_{input}\ y^{-1}$	500 (~ 665 MW_{th})
Investment costs[b]	$€\ T_{input}^{-1}\ y^{-1}$	102,5
O&M costs	$€\ T_{input}^{-1}$	26,61
Yield of product	$T\ T^{-1}$	0,39
By-product (oilseed pulp/cake)[g]	$T\ T^{-1}$	0,59
Transesterification (oil seeds)		
Scale	$kT_{input}\ y^{-1}$	100 (~ 134 MW_{th})
Investment costs[b]	$€\ T_{input}^{-1}\ y^{-1}$	200
O&M costs	$€\ T_{input}^{-1}$	80,60
Yield of product	$T\ T^{-1}$	1,00
By-product (glycerine 80%)[g]	$T\ T^{-1}$	0,11
Transesterification (used oil/fats)		
Scale	$kT_{input}\ y^{-1}$	50 (~ 67 MW_{th})
Investment costs[b]	$€\ T_{input}^{-1}\ y^{-1}$	300
O&M costs	$€\ T_{input}^{-1}$	88,66
Yield of product	$T\ T^{-1}$	1,00
By-product (glycerine 80%)[g]	$T\ T^{-1}$	0,10
Ethanol from sugars		
Scale	$kT_{input}\ y^{-1}$	100 (~ 54 MW_{th})
Investment costs	$€\ T_{input}^{-1}\ y^{-1}$	163
O&M costs	$€\ T_{input}^{-1}$	67,20
Yield of product	$T\ T^{-1}$	0,29
By-product (sugar crop pulp & vinasses)[g]	$T\ T^{-1}$	0,31 & 0,12
Ethanol from starch		
Scale	$kT_{input}\ y^{-1}$	100 (~ 54 MW_{th})
Investment costs[b]	$€\ T_{input}^{-1}\ y^{-1}$	264
O&M costs	$€\ T_{input}^{-1}$	92,20
Yield of product	$T\ T^{-1}$	0,35
By-product (Stillage)[g]	$T\ T^{-1}$	0,28
Second generation		
Ethanol from lignocellulose		
Scale	MW_{th}	200
Investment costs[b, h]	M€	228
O&M costs	$M€\ y^{-1}$	23
Fuel Efficiency	$GJ_{EtOH}\ GJ_{feedstock}^{-1}$	0,39
By-products (electricity)[g]	$GJ_{electrcity}\ GJ_{feedstock}^{-1}$	0,105
Fischer-Tropsch from lignocellulose		
Pre-treatment[j]		
Scale	MW_{out}	150
Investment costs[i]	M€	30
O&M	$M€\ y^{-1}$	9
Fuel Efficiency	$GJ_{treated\ feedstock}\ GJ_{feedstock}^{-1}$	0,95
Fisher-Tropsch synthesis		
Scale	MW_{th}	200
Investment costs[i]	M€	223
O&M	$M€\ y^{-1}$	13
Fuel Efficiency	$GJ_{FT}\ GJ_{feedstock}^{-1}$	0,53
By-products (electricity)[g]	$GJ_{electrcity}\ GJ_{feedstock}^{-1}$	0,033

A – For all technologies included, 8000 full load hours and an economic life time of 20 years was assumed, except for the pre-treatment step for Fischer-Topsch where a lifetime of 10 year is assumed see under j.

B – All investment costs are corrected with an annuity following the specifications under a with an interest rate of 6%.
C – All process steps marked with an d from the Inside battery limit (ISBL) which make up 50% of the investment cost, the outside battery limit make up the other 50% of the investment cost (see under e) this total is excluding owners cost, which add an additional 20% (see under g).
D – OSBL = Outside battery limit. This cost factor comprises "items like auxiliary buildings, site improvements, utility and service facilities, storage and distribution, land purchase. In this assessment the OSBL costs are fixed at 100% of the ISBL costs. For typical chemical plants, the OSBL costs are only 20% of the ISBL costs. However, in a GTL plant the volumes of the side streams are very high, i.e. the oxygen and nitrogen from the ASU as well as water by-product from the FT synthesis. Handling and treatment of these streams require correspondingly more auxiliary operations" quote from (Boerrigter, 2006).
E – EPC = Engineering, Procurement, and Contracting or turn-key delivery. These EPC costs are in most cases referred to when investment costs of GTL plants are published.
F – Owner costs comprise (a) Indirect Costs for up-front R&D, up-front license, engineering, construction, contractor's fee, and contingencies, (b) Working Capital, i.e. inventories, salaries and wages due, receivables less payables, and cash, and (c) Start-up Costs, i.e. modifications, start-up labour, and loss in production. In this assessment the Owners Costs are fixed at 20% of the ECP scope.
G – Residual streams from the processes are assumed to be sold on the market to form a reimbursement to the overall production costs. The following market prices for residual streams are assumed: oilseed pulp/cake 63 € tonne-1, glycerine (80%) 120 € tonne-1, sugar crop pulp and vinasses 75 € tonne-1, Stillage 105 € tonne-1 and electricity 47,7 € MWh-1
H – Lignocellulose ethanol capital costs are built-up of Pre-treatment (25%), hydrolysis and fermentation (3%), Upgrading (7%), Residuals (12%) and Power Island (54%).
I –Fischer-Tropsch' capital costs are built up of an Air Seperation Unit (ASU) (12%), Gasifier (8%), H2 manufacturing and syngas conditioning (3%), rectisol unit (9%), Fischer-Tropsch synthesis (6%), Product upgrading (4%), OSBL (42%) and Engineering, Procurement and contracting (EPC) (17%).
J – Lifetime for the pre-treatment step has an assumed lifetime of 10 years instead of 20 years as is assumed for all the other processes.

For technological learning, the ethanol process from sugar crops and the one from starch crops were taken as one process (entity). The progress ratio for bioethanol was estimated at 80%, based on the experience of learning in bioethanol production in Brazil (van den Wall Bake et al., 2009) and the US (Hettinga, 2007). For estimation of the cumulative production volume, all ethanol produced in Europe from sugar and starch is considered, instead of only that for fuel purposes. The rationale for this is that the fermentation process learns from both the production of ethanol for fuel and ethanol for other purposes. Production data were obtained for the 1970-2000 period (United Nations, 2007) and for the 2001 – 2004 period (EUobserver, 2006; Miguel, 2006). Based on the 1970 – 2004 period production volumes were extrapolated back to 1950. For this (re)constructed historic time period, cumulative production – up to and including 2004 – in Europe amounts to almost 1.35 EJ (see Table 6-3).

Lignocellulose to ethanol. Process description – Production of bioethanol from lignocellulose (LE) material comprises of three major steps (1) pretreatment of the lignocellulose material, (2) hydrolysis of the lignocellulose to break it down into sugars (C5 and C6-sugars) and (3) fermentation of the sugars to convert it into bioethanol. Various processes are available to pre-treat lignocellulose feedstocks (Mosier et al., 2005) that are required to reduce size and improve surface-to-volume ratio to make it suitable for hydrolysis. Different levels of process integration, of the hydrolysis and fermentation processes, are possible that could reduce the number of reactors needed and so reduce associated installation costs, reduce process duration and raise overall process efficiency (Hamelinck et al., 2005). Data used in this study are based on a Simultaneous

Sacharification and Fermentation (SFF) configuration, which was already considered state-of-the-art in 1996 (Lynd, 1996; Lynd et al., 2005), although this is also disputed (Froese et al., 2008).

Investment and O&M costs – Capital and operation costs are based on a bottom-up engineering study (Kuijvenhoven, 2006; Reith et al., 2007). Other factors such as process efficiency and excess electricity output, potentially available to deliver to the grid, are based on (Hamelinck et al., 2005; Reith et al., 2007), see Table 6-2. Based on the production costs that follow from the investment costs a scale- dependant cost development was estimated. A scale factor of 0.7 was used to calculate production costs at different scales. The assumed doubling time for both technologies is set at 5 years. The speed of up-scaling can be restricted, either by the market share one single plant can serve or if a maximum scale is reached (Table 6-2). The maximum scale was set rather modest (e.g. compared to a 'conventional' oil refinery scale) as larger plants would barely reduce specific investment costs further, while the required biomass logistics and storage would become increasingly complex.

Scale-independent technological improvement and cost reduction prospects – A key challenge is the ability to (efficiently and) cost competitively ferment pentose (C5) sugars (Lynd, 1996). Research and development efforts are directed at genetically engineering bacteria to meet these requirements, reports on its progress to date vary (Hahn-Hägerdahl et al., 2007). Pre-treatment, a process step to size the lignocellulose feedstock to make it susceptible to enzyme attack (Wyman, 1999) is currently both capital and energy intensive. Future requirements to particle size may be relaxed due to improved hydrolysis thereby reducing energy and cost consumption and, consequently, improving performance (Hamelinck et al., 2005). More efficient (re)use of solvents can reduce expenses. Different levels of system integration of the hydrolysis and fermentation process can reduce system size, process duration, increase overall process efficiency and consequently improve cost performance.

Estimates for the cost learning potential are based on a process-step specific overview (Wyman, 1999). Estimated cost reduction potential for the processes are: pre-treatment (33%), SSF fermentation (28%), distillation (13%), Other processing (13%), pentose conversion (7%), cellulose production (6%) and power cycle (3%). The progress ratio is derived by applying the cost improvement potentials per process step to the relative contribution of these steps to the overall investment costs, as presented in Table 6-1. This approach results in a scale independent learning progress ratio in the range of 99% (Table 6-2).

Lignocellulose to Fischer-Tropsch. Process description – The process from biomass-to-Fischer Tropsch (FT) diesel comprises of three major steps, (1) the pre-treatment of the raw feedstock, (2) the gasification of lignocellulose material to syngas (H_2 and CO) and (3) the FT reactor where the syngas is used to synthesize FT (synthetic) diesel, although a multitude of end products can be synthesized, e.g. kerosene. Various process types exist (e.g. atmospheric or pressurized, air- or oxygen blown), each with specific advantages and disadvantages (Hamelinck and Faaij, 2001). The data used in this analysis (Bergman et al., 2005; Boerrigter, 2006), assume biomass pretreatment through drying, torrefaction and pelletisation, followed by an oxygen-blown entrained-flow gasifier for syngas production. The resulting raw biosyngas is cooled, conditioned, cleaned from the impurities, and used for FT synthesis to produce $C5^+$ liquid fuels.

Investment and O&M costs – Analysis is based on cost data (Boerrigter, 2006) of recently realised or planned gas-to-liquids (GTL) projects. For the required biomass-to-liquids (BTL), assumptions have been made concerning process steps that have different capital costs for BTL compared to GTL. A cost-breakdown is presented in Table 6-2. For scale-dependent costs, a scale-factor of 0.7 was used up until 900 MW_{th}. The entrained-flow gasifier can be scaled up to a size of several GW_{th} (Boerrigter, 2006), but with increasing size, other parts of the installation (e.g. the pretreatment and gas cleaning sections) have to be built in parallel, which diminish the overall scale effect (Tijmensen et al., 2002; Hamelinck et al., 2004; van Vliet, 2007). Therefore, from 900 MW_{th} onwards, a scale factor of 0.85 for overall investment costs was used. The maximum size was set at 3.2 GW_{th} following the same reasoning as for advanced ethanol production. The scaling curve (presented in Figure 6-3) and corresponding investment costs up to 3.2 GW_{th} compares well to other studies (Hamelinck et al., 2004; van Vliet, 2007).

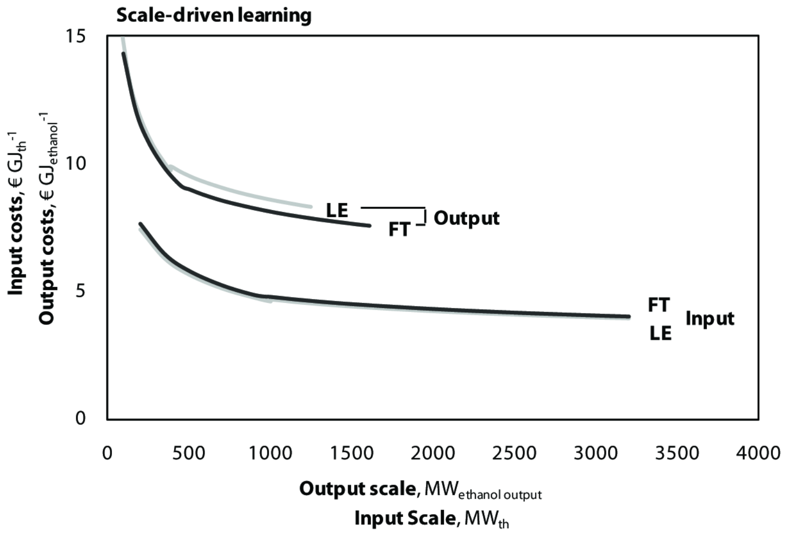
Table 6-3 Market-driven and scale-driven learning parameters (BASE-case).

Technology	**Market-driven learning**		**Scale-driven learning**			
	Initial cum. installed capacity 2005	PR	Scale factor	Maxim-um scale2	Maximum market share	Doubling time
	MW_{th}	-	-	*MW_{th}*	*%*	*years*
First generation						
Transesterification (oil seeds and oils/fats)	214,5 (PJ)	90%	n.a.	n.a.	n.a.	n.a.
Sugar	675 (PJ)	80%	n.a.	n.a.	n.a.	n.a.
Starch ethanol	675 (PJ)	80%	n.a.	n.a.	n.a.	n.a.
Second generation						
Lignocellulose ethanol	200	99%	0,7 (≤ 1000 MW_{th}) 0,85 (> 1000 MW_{th})	3200	5	5
Lignocellulose Fischer-Tropsch	200	98%	0,7 (≤ 900 MW_{th}) 0,85 (> 900 MW_{th})	3200	5	5

n.a. = not applicable

Scale-independent technological improvement and cost reductions prospects – Several technologies considered for FT-production are not yet fully proven or commercially available: pressurised (oxygen-blown) gasifiers still need further development. A very critical step is gas cleaning, and it still has to be proven whether the (hot) gas cleaning section is able to meet strict cleaning requirements for reforming, shift and synthesis. Another critical factor is the catalyst selectivity to increase $C5^+$ output. Based on these possible technological improvements, a (relatively modest) progress ratio for scale-independent learning was assumed in the range of 98% (see Table 6-2) .

Scale-driven learning for lignocellulose ethanol and Fischer-Tropsch – Figure 6-3 displays the scale dependant learning curve for the conversion technologies LE and FT. The lower two curves represent the conversion costs in relation to the (thermal) feedstock input (MWth in) scale and conversion costs for feedstock input (€ (GJfeed in)$^{-1}$). The two upper curves present the fuel production costs ((€ (GJfuel out)$^{-1}$) for the respective fuel output scales



(MWfuel out).

Figure 6-3 Scale-driven learning curve for the lignocellulose-to-ethanol (LE) and lignocellulose-to-Fischer-Tropsch (FT) conversion technology.

6.4 Results and discussion

This section presents the BASE case model run (4.1) and the outcomes for the sensitivity analysis (4.2). Other BioTrans results are presented elsewhere in this volume (Lensink et al., 2010; Londo et al., 2010).

6.4.1 BioTrans output under BASE case assumptions

Under BASE case assumptions (Table 6-4) biodiesel is the most cost effective fuel, completely dominating the market when only in competition with bioethanol (Figure 6-5-a). The better cost performance of biodiesel over bioethanol is explained by lower feedstock costs for oil crops compared to sugar and starch crops and by relatively lower capital and operational expenses for transesterification of oil to biodiesel compared to (hydrolysis) and fermentation of sugar and starch crops to bioethanol. The initial production cost advantage and market domination of biodiesel blocks opportunities for bioethanol to learn and thereby to decrease costs.

Under the BASE case assumptions both 2nd generation biofuel production routes are available for market introduction (when cost competitive) by 2010. This, immediately upon availability, results in market introduction of FT in 2010 at costs of 19.3 € GJ^{-1}. Given the ambitious (target-driven) demand for biofuels high cost oil-crop resources are required to meet this supply. So, despite fairly high FT production costs, it competes with the most costly biodiesel immediately in 2010. From 2010 onwards, FT gradually increases its market share, to reach a 64% share by 2030. The dominance of produced volumes FT over biodiesel until 2030 is driven by rapid cost reductions of both the feedstock and conversion costs for FT. Although FT is competitive with the most expensive biodiesel, on average overall FT costs are still higher then biodiesel costs (see Figure 6-4-a). Note that absolute biodiesel volumes increase continuously.

LE does not enter the market due to higher initial (2010) production costs. As the BioTrans model uses a least cost optimization routine, no market introduction is reached. Also two other features of the model cause it to make 'radical' choices: the fact that the model is myopic (short-sighted) and because endogenous learning creates path-dependencies. These mechanisms are further discussed in section 4.2.3.

6.4.2 Sensitivity analysis

Aim of the sensitivity analysis is (1) to explore how variations in parameter values affect the fuel production cost levels and their improvement potential over time, and (2) what biofuel mix is obtained under a set of parameter values and how it relates to (and differs from) the baseline (BASE case). Parameter values of four drivers, that impact on the market dynamics, are varied: (1) investment costs (2) progress rates, both scale and experience learning, (3) timing of market introduction of technologies and (4) the existence of separate supply markets for diesel and gasoline substitutes, see Table 6-4.

Investment costs. Investment and operation costs for all technologies considered in the modeling are subject to uncertainties. Most data used as basis for modeling originated from studies carried out between 2000 – 2004. However, since then surging (volatile) raw material prices, increased demand for power technologies (e.g. boilers and gas turbines) and a fluctuating Dollar-Euro exchange rate have impacted on the investment costs for power technologies. At the moment of writing, the global economic downturn (crisis) slows off demand thereby bringing prices back to moderate levels which could bring down investment costs in the near future. This all the more illustrates the need to investigate the implications of price fluctuations on market dynamics. Because the production of advanced biofuels is more material and therefore capital intensive than 1st generation biofuels, high prices provide a relative advantage for 1st generation biofuels.

Because of the multitude of drivers affecting production cost levels, a broad range was chosen to explore sensitivities. Two approaches were followed. (1) the effect of integral higher investment costs for all technologies, driven e.g. by increased steel prices, was explored.

Table 6-4 Parameter variations as used in the sensitivity analysis.

Subject/case	parameter	BASE case	Case value
Investment costs			
Investment costs doubled	Investment costs	As presented in Table 6-2	Double the values as presented in Tabe 2
20% lower 2nd gen. investment costs	Investment costs	As presented in Table 6-2	Investment costs FT and LE reduced by 20%
Learning			
Improved learning 2nd gen.	Progress ratios (PRs)	As presented in Table 6-3	All PRs set to 1, PRs for FT and LE set to 0,95
Slower up-scaling 2nd gen.	Doubling-time FT and LE	5	10
Market introduction			
Delayed availability FT	Year of market availability FT	2010	2020
Delayed FT + improved eff. LE	Year of market availability FT Fuel efficiency LE	2010 0,39	2020 0,47
Subtarget			
Subtargets for gasoline and diesel substitutes	Subtargets gasoline and diesel substitutes	No differentiation	20% gasoline substitutes and 80% diesel substitutes

As a first order approach, investment costs for all technologies were doubled. (2) A second case was explored in which investment costs for 2nd generation technologies were lowered by 20%, compared to the BASE case. This is in line with investment costs figures in literature, e.g. (Aden et al., 2002; Hamelinck et al., 2005). Figure 6-5-d displays the case where investment cost are doubled (invest cost double case). Two observations stand out in comparison with the BASE case: (1) introduction of FT production is delayed until 2017, explained by a higher increase in conversion costs for 2nd compared to 1st generation biofuels. Overall FT production cost increases by 42% compared to biodiesel production by only 8%, as seen in Figure 6-4-d. (2) The delayed FT introduction stimulates biodiesel production, up to and after 2017, mainly because the use of high-cost oil crop feedstocks remains cost competitive even longer. Figure 6-5-c depicts the investment cost – 20% off 2nd generation case. Due to lower conversion costs FT production is more cost effective, to compete with biodiesel early on, hence expanding its share in the biofuel mix at the expense of biodiesel production, reaching a 78% market share by 2030.

Results show that an integral increase of investment costs strongly favours biodiesel production. Furthermore, because higher investment costs raise overall production costs, especially for 2nd generation technologies, it weakens the relative competitiveness with fossil transport fuels (see Figure 6-4-d). If, on the other hand, investment costs are reduced for 2nd generation technologies, the production cost gap with biodiesel can be closed earlier on, paving the way for accelerated implementation of FT production.

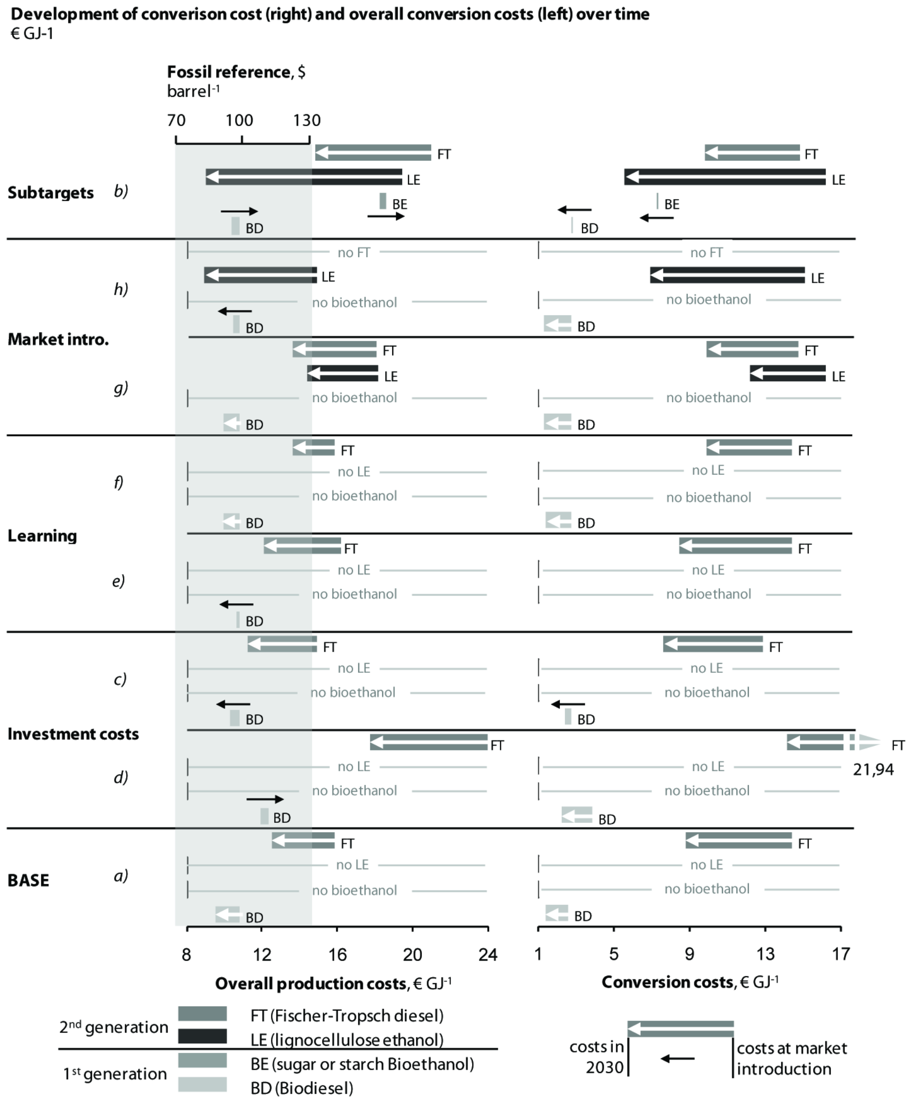


Figure 6-4 Overview of the *conversion costs* and the *overall production costs* of biofuels under the BASE case and cases explored in the sensitivity analysis cases.

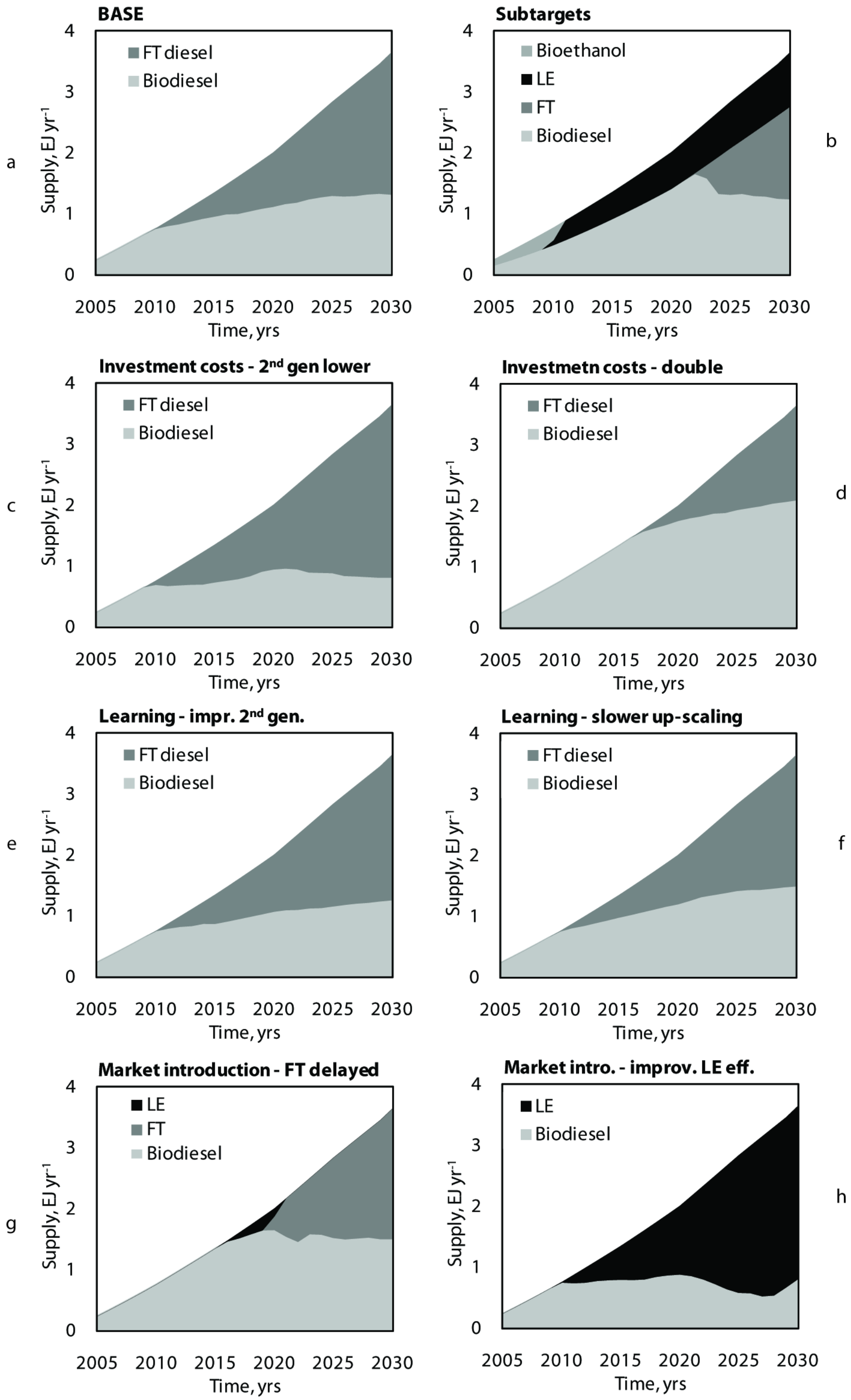


Figure 6-5 Biofuel mix for satisfying demand. Sensitivity analysis output for multiple parameter variations.

Scale-driven and experience-driven learning. First generation biofuel conversion technologies are not assumed to achieve any further substantial scale increases over time. For the extent that they do, resulting cost reductions are included in the experience-driven (endogenous) learning parameter. Advanced conversion technologies, on the other hand, are considered to increase in scale considerably over time. Under BASE case assumptions scale doubling takes place every 5 years. To explore how differences in up-scaling speed impact on the results the doubling-time is varied between 3 and 10 years.

Figure 6-5-f depicts the slower up-scaling case where the doubling-time is set to 10 years. It can be seen that the effect on the moment of market introduction and the share in the biofuel mix of FT is hardly affected. The FT conversion costs, however, are affected as can be seen in Figure 6-4-f. Also a faster up-scaling case was assessed, where the doubling time was set at 3 years. This case is not depicted since no significant changes were observed relative to the BASE. Figure 6-5-e depicts the learning case where the progress ratio for both advanced technologies (LE and FT) was set at 0.95. Again, no significant change is observed. This is mainly due to the fact that the effect on cost reduction of up-scaling is much stronger than that of experience learning.

Timing of market introduction. The moment in time that advanced biofuel production routes will become (commercially) available is by definition uncertain. The effect of a relative earlier market introduction of one technology relative to the other can seriously affect its share in the future biofuel mix. This is especially true if no separate gasoline and diesel substitute markets are present. In this case technologies can be considered to supply a homogenous product (there obviously is a difference between supplying 'a' biofuel versus supplying either a diesel or gasoline substitute as will be elaborated on in the next paragraph). When introduced in the market simultaneously, an initial fuel cost advantage will make the model to prefer one technology over the other causing only the preferred technology to penetrate the market (and thus let it learn and reduce costs); blocking the way for market introduction of the competing technology. This mechanism of lock-in is dominantly present in the BioTrans model due to its myopic foresight and least cost optimization criterion; leading to path-dependencies.

FT production is the preferred advanced biofuel option, due to a initial cost advantage, in the base case. However, as discussed in section 4.2.1, this is to some degree uncertain. To explore a scenario where LE enters the market before FT, two parameters are varied. Firstly, the market availability of FT is delayed to 2020. Secondly, the efficiency of LE is increased to 47% (in line with (Hamelinck et al., 2005; Lynd et al., 2005)), effectively stimulating both energy and cost performance. Figure 6-5-g displays the earlier market intro 2nd ethanol case, where the market introduction of FT is delayed by 10 years. Three observations stand out compared to the BASE case: (i) Due to high fuel costs for LE compared to 1st generation biodiesel, market introduction of lignocellulose ethanol is late (2016). (ii) This late market introduction and, subsequently, use of (more) high-cost oil crop feedstock results in significantly more biodiesel production to meet demand, up to and after 2016. (iii) Immediately upon the 'new' year of market availability for FT (2020) it makes a market entrance. This shows that (scale and non-scale related) learning of LE in the period from its market introduction to 2020 has not been sufficient to out-compete production costs for FT at its market introduction, even though both routes use the same feedstock base (at equal costs) to produce fuels. Figure 6-5-h shows the case where the conver1ion efficiency for lignocellulose ethanol is raised from 39% (BASE case) to 43% while maintaining late FT availability in 2020. With the improved efficiency lignocellulose ethanol now has an improved cost performance and is able to stay ahead of FT for the whole period. This illustrates the importance of the timing of market introduction; also for the long(er) term prospects for both technologies.

Subtargets for biodiesel and bioethanol. In the BASE case and all other cases assessed so far, a single biofuel target is used (as is currently the case in the EU), i.e. no differentiation between sub targets for diesel and gasoline substitutes is assumed. For two reasons it is deemed appropriate to explore effects of a differentiated biofuel target for diesel and gasoline substitutes. Firstly, currently separate markets exist for transport fuels. Secondly, a differentiated target could create separate (niche) supply markets, thereby diversifying the production portfolio, increasing market resilience, spreading risk and preventing lock-in.

To evaluate which biofuel mix establishes under separate targets, the model is run with a constant 80%-20% target, respectively for diesel and gasoline substitutes. All other parameter values are identical to the BASE case. Figure 5-b depicts this sub-target case. What stands out in this result is: (i) Starch and sugar based ethanol make it into the market only because of the target-driven demand for ethanol (as a gasoline substitute) and the unavailability of LE, until 2010. (ii) Directly upon commercial availability in 2010, LE enters and dominates the ethanol market share, due to a substantial production cost advantage compared to bioethanol (see Figure 4-b). (iii) For the diesel substitute market share, biodiesel is the most cost competitive option even long after FT is available for market implementation. FT is only introduced into the market in 2022 compared to its immediate introduction in 2010 in the BASE case. This observation is mainly explained by two mechanisms. Firstly, because the diesel substitute market is smaller in absolute terms, biodiesel production can rely on a relatively large low-cost feedstock potential. This makes biodiesel the preferred option for a longer period. Secondly, because LE is introduced into the market early, it starts using low-cost lignocellulose feedstocks (mainly forestry and agricultural residues) the same feedstock that FT production requires. Because with LE production lignocellulose feedstock becomes increasingly expensive, it adds to the delay of the FT route into the biofuel mix.

These results illustrate that regarding competition between bioethanol and LE, the latter is more cost effective directly upon availability of the technology. This in contrast to the competition between the two diesel substitutes where production costs are closer together.

6.4.3 Methodological discussion and recommendations for further research

Modeling feedstock cost developments – Developments in the production of (bioenergy) feedstocks were in this study modeled exogenously. The approach was significantly refined, compared to earlier efforts, by differentiating development speeds per crop. A next refinement step could be the modeling of feedstock cost development endogenously. This requires gaining insight into developments of the relation between historic production cost and cumulative produced volumes.

No optimal path to a future optimal solution can be determined – this is due to the myopic foresight and the model requirement to meet the increasing biofuel target each year based on the least-cost option(s). Moreover, several solutions may be near optimal, following different transition paths and arriving at different end solutions, to comparable costs (Lensink et al., 2009).

Prices versus costs and exchange rate fluctuations – Input data stem from a range of literature sources. Two cost data aspects introduce uncertainty (i) the difference between the use of costs versus prices and (ii) a changing euro-dollar exchange rate. Investment costs, presented in literature, can either relate to production costs but in some cases relate to (market) turnkey prices. Production costs reflect the (actual) expenses that arise from labour input, raw material use etc.. Turn key prices, on the other hand, also include margins for the value that is added along the supply chain. One reference (Hamelinck et al., 2005) specifies the uncertainty range in (specific) investment and operation costs to be in the order of +/- 30%. Price data can be assumed to have even greater uncertainty. Cost and price data is mainly collected for the 2002 – 2006 period in either euros or (US) dollars. Given the strong (US dollar to euro) exchange rate fluctuations this introduces additional uncertainty.

Electricity reimbursement influences competition between technologies – Both the advanced conversion technologies produce power and heat, mainly for system requirements. Depending on residual streams and process optimization, additional electricity (and heat) can be produced. With FT production, it is possible to optimize on fuel output, with only limited electricity output. The production of LE, on the other hand, produces considerable amounts of excess electricity, available from the non-fermentable lignin fraction. This electricity can potentially be delivered to the grid and thus form a reimbursement to overall fuel production costs. Although the influence of a varying electricity price – market price, reimbursement tariff or a combination – is not assessed in this analysis it may have a profound effect on the competition between technologies.

Standing capacity prevents radical technology switch – BioTrans fills in the demand for biofuels every year with the least cost option, without taking into account the standing production capacity. This can lead in theory to the situation where a technology is installed in one year and is substituted the next year by a (slightly) more cost-competitive option. In reality, the less cost-competitive option can, however, still be profitable (even more so than the more cost-competitive option) if investment cost have already been depreciated. Because production costs rather than profit (gained market price minus costs) is used for optimization, this effect is not included. Another driver to continue operation of a less cost effective (or profitable) technology is the fact that the investment has to be earned back. Retrofitting or upgrading older (depreciated) installations can be another option for reducing investment and operational costs, especially for 1st generation conversion technologies. While implementing this effect in future versions of BioTrans is recommended, in the current analysis we deem this issue of minor importance, as in none of the cases significant amounts of capacity (e.g. >0.5 EJ y^{-1}) are rapidly replaced.

Separate gasoline and diesel substitute markets – In the modeling, no distinction is made between markets for gasoline and diesel substitutes. On the one hand this reflects current European policy, not differentiating the biofuel target. On the other hand, at present separate transport fuel markets exist. Differentiated targets could stimulate diversification of feedstock and technology use and thereby, in an up-coming market, prevent lock-in of suboptimal options.

6.5 General discussion, conclusions and policy implications

Based on the model results, the following conclusions are drawn:

- The potential to reduce conversion installation costs between 2005 and 2030 is considerably larger for advanced biofuel options than for 1st generation biofuels. Key driver for reducing advanced biofuel conversion costs is up-scaling from pilot scale to 'full' industrial scale, in the base case assumed to take approximately 20 years. Production cost reduction potential for 1st generation biofuels is limited.
- At moderate investment costs advanced biofuel options enter the market upon availability. With increasing investment costs for all technologies, e.g. steered by higher steel prices, 1st generation biofuels have a relative advantage, delaying the diffusion of advanced biofuels. Results suggest that this delay could range from several years up to a decade. Given the strong effect of changing investment costs on 2nd generation market penetration, potentially investment subsidies for 2nd generation biofuel plants could be an important prerequisite for a successful market introduction of advanced biofuels.
- Domestic European feedstock resources are relatively scarce at ambitious biofuel targets, which require the use of more expensive resources (produced on more expensive land or regions). Expenses for resources make up the majority of 1st generation biofuel costs. This stimulates the production for advanced biofuels in two ways (i) woody and grassy resources have a higher productivity and (ii) resource expenses are only a minor part of advanced fuel costs.
- In the competition for market diffusion, the relative moment of market implementation plays a key role. When a technology is implemented it can start up-scaling and gain operational experience, steadily decreasing production costs. When the period between the market penetration of two competing technologies prolongs, the chances for the last technology to be implemented diminish. Policy that aims at preventing lock-in should focus on facilitating opportunities to establish technology portfolios. One measure could be differentiation of a biofuel target for gasoline and diesel substitutes for advanced biofuels.
- Production cost levels for conventional crops and dedicated bioenergy crops have the potential to be considerably reduced, in the range of a 30% reduction over 25 years. Feedstock production cost developments were modeled exogenously with crop-specific learning rates. This is a major refinement, compared to earlier modeling endeavors, which more adequately takes into account the different stages of development between crop production systems.
- The production of advanced biofuels is more material and therefore capital intensive than 1st generation biofuels. For this reason, fluctuating raw material (and other) prices impact on the competition between 1st and 2nd generation biofuels. Results indicate that high price levels provide a relative advantage to 1st generation biofuels and, vice versa, low price levels stimulate 2nd generation biofuels. Model outcomes show that a mere 20% decrease in 2nd generation installation investment costs lead to a 50% market share already in 2020 (instead of 2025 in the BASE case).
- Overall production costs for 1st and 2nd generation biofuels will, for most cases, be cost competitive with fossil transport fuels, in the range of 70–130 \$ barrel^{-1} (7.8–14.5 € GJ^{-1}) oil equivalent, by 2030. First generation biodiesel show stable overall production costs of around 100 \$ barrel^{-1}. Advanced biofuel options start-off more expensive, in

the range of 180 \$ barrel^{-1} (20 € GJ-1), but have opportunities to reduce costs significantly, 30 to 60%, to become cost competitive with fossil transport fuels in the range of 70–130 \$ barrel^{-1} (7.8 – 14.5 € GJ^{-1}).

The modeling of production cost developments required different approaches for various biofuel options. The most challenging task was to adequately model advanced biofuel options, because of the limited availability of (historic) production costs data related to installed capacity. This challenge was satisfactory met by the developed approach (combining bottom-up and top-down insights). Even though, this approach demanded extensive bottom-up engineering data and adaptations to the modeling routine. Furthermore, the inclusion of several parameters (e.g. progress ratios, scaling laws, time of market introduction etc.) in the sensitivity analysis allowed for an exploration of their individual impact on cost developments and market diffusion.

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7 Summary and Conclusions

7.1 Bioenergy in Europe and crucial issues relating to its expansion

Fossil resources dominate the global energy system and are used among others as transport fuels, in electricity generation as a feedstock for plastics, chemical and fertilizers. Dominant reliance on fossil fuels cannot be sustained indefinitely due to the finiteness of fossil resources and its adverse implications to the earth's climate that stem from substantial increases of fossil fuel use which led to a rise in anthropogenic carbon dioxide emissions and as a result in higher atmospheric concentrations with implications to the earth's climate. Greenhouse gases are emitted to the atmosphere through the combustion of hydrocarbons, deforestation, animal husbandry and fertilizer use. These energy related GHG emissions can amongst others be reduced by modern bioenergy applications. Bioenergy refers to a wide range of biobased feedstocks and technologies. Common biomass feedstocks include residual streams from forestry and agriculture, dedicated production by annual or perennial energy crops and biomass waste streams. Bioenergy technologies produce power or heat directly or produce gaseous, liquid or solid biofuels.

Both global and European primary biomass use are accelerating. In Europe, this has largely been on the account of environmental and specific biofuel policies. Several benefits of bioenergy drive its (increasing) use. Firstly, bioenergy can substitute fossil fuels, including oil, the resource most short in global reserves. Secondly, when sustainably produced bioenergy avoids GHG emissions. Thirdly, biomass feedstocks can be integrated in many existing energy infrastructures. Biofuels can directly replace gasoline and diesel and thus mineral oil. However, with the recent increase of modern bioenergy use several drawbacks have become apparent, it can lead to changing land use patterns, deforestation, *etc.* which in turn can lead to negative ecological impacts. Also, the competition for feedstocks and land between bioenergy and food can lead to undesired impacts.

Europe plays an important role in the (further) development of bioenergy due to its ambitious renewable energy policies and its state-of-the-art agricultural sector. Over the past decades, Europe's agricultural output has increased significantly mainly from increasing productivities facilitated by a strong common agricultural policy (CAP). The European commission envision a large role for biomass resources to reach their mitigation target by 2020. To assess the opportunities, limitations and implications of extended bioenergy use in a European context several crucial issues require in-depth and integrated analysis:

- For example, further scrutiny is needed on the key driving forces that steer future biomass resource potentials and into the spatial distribution of these resources in Europe.
- The extent to which agricultural productivities can be increased, and the rate at which this can be established developed into key issues in the debate surrounding bioenergy potentials and need further assessment.
- Furthermore, integral evaluation of specific environmental impacts associated with expanded bioenergy production and rationalisation of agriculture is needed.
- To assess the current economic performance of bioenegry options, further research is needed on the prospects for cost reduction of dedicated perennial energy cropping

systems and (advanced) bioenergy technologies to reduce future production costs. Especially given their expected importance for future biomass supplies and limited commercial experience to date.

- Related to improvements in this economic performance, the complex interactions between competing renewable or fossil technologies can be modeled to gain insight into technology diffusion patterns (market penetration).

7.2 Aim and research questions

The main objective of this thesis is to evaluate development pathways for bioenergy in Europe by assessing preconditions for its development, an economic outlook for such development and an assessment of its environmental implications. Three main questions have been formulated addressing the knowledge gaps identified in the previous section:

1. What is the techno-economical biomass production potential in Europe, how is it spatially distributed and what driving forces steer its development over time?

2. To what extent can biomass potentials be realized sustainably in Europe without imposing adverse environmental impacts and conflicts with food production?

3. What are possible diffusion pathways of different competing biofuel production routes distinguished between developments in feedstock and conversion, given their current and future economic performance?

	Q1	Q2	Q3
Chapter 2: Biomass resource potential and costs	•	•	•
Chapter 3: Productivity developments in European agriculture	•	•	
Chapter 4: Environmental impacts of integrating biomass production into European agriculture		•	
Chapter 5: Learning in dedicated wood production systems			•
Chapter 6: Competition between biofuels	•		•

7.3 Summary of the results

Chapter 2 addressed research questions 1, 2 and 3 by assessing the European biomass resource potential and costs. Three scenarios were constructed that considered different growth rates for crop yields and livestock production. Results indicate that the ultimate total available land for bioenergy crop production – following a 'food first' paradigm – could amount to 90 million hectares by 2030; 66 million hectares of arable land and 24 million hectares of pastures. Primary biomass feedstock supply potential from dedicated energy crops varies between 1.7 and 12.8 EJ y^{-1}, depending on which energy crop is produced and the scenario chosen. Agricultural and forestry residues can respectively add a maximum of 3.1–3.9 and 1.4–5.4 EJ y^{-1}. With regard to production costs, first generation feedstocks are available at 5–15 € GJ^{-1} compared to 1.5–4.5 € GJ^{-1} for second generation feedstocks like fast growing grasses and tree species. Costs for agricultural residues are 1–7 € GJ^{-1} and forestry residues 2–4 € GJ^{-1}. Large variation exists in biomass production potential and costs between European regions. Regions that stand out with respect to high potential and low costs are large parts of Poland, the Baltic States, Romania, Bulgaria and Ukraine. In Western Europe, France, Spain and Italy are moderately attractive following the high potential & low cost criterion.

Based on the crucial role that productivity developments in agriculture have on the biomass resource potentials this issue was further evaluated in **Chapter 3**, addressing research questions 1 and 2. In this chapter it was assessed if, how fast and to what maximum level yield improvements can be realized in Europe in the coming decades. Historic developments in European crop and animal protein productivity between 1961 and 2007 show an average mean annual growth rate of 1.6%. In relative terms developments are slower on average in the Netherlands and France at 1.0% y^{-1} than in Poland and Ukraine (USSR) at 2.2% y^{-1}. In absolute figures, however, growth has been considerable in Western European countries (WEC) and modest in the central and Eastern European countries (CEEC). Yield trends further show that significant yield changes can be realized over a short period of time. Positive growth rates of 3–5% y^{-1} were reached in several countries and for several crops in specific decades. In Eastern European countries during their transition in the 1990s, negative growth rates as low as −7% y^{-1} occurred.

Chapter 4 addressed research question 2 by evaluating the environmental impacts associated with the expansion of energy crop production on European croplands. Simulations account for four key developments that steer the (net) GHG emissions of European agricultural land use, either creating additional emissions or preventing them compared to continuing at current levels. These developments are: (1) gradual intensification of agricultural production, (2) implementation of structural land management improvements, (3) gradual expansion of dedicated energy-crop production on lands not needed for food production, and (4) the mitigation of fossil fuel emissions in transport when replaced by biofuels based on these energy crops. Maintaining the current agricultural intensity level results in 4.9 $GtCO_2$-eq. of cumulative emissions from the European land use by 2030. Intensified food production and energy crop production on freed cropland in combination with mitigation measures can significantly affect cumulative emissions. When oil, starch or and sugar crops are used as energy crop on this freed cropland, cumulative emissions of agricultural land use are reduced to 1.9, 1.5 and 2.1 $GtCO_2$-eq., respectively. When perennial crops are applied, cumulative emissions are more than outbalanced and agricultural land use becomes a net sink, with cumulative emission mitigations of 3.3 and 4.5 $GtCO_2$-eq., for grass and wood crops respectively.

Chapter 5 addressed research question 3 by assessing the learning potential of dedicated wood production systems to raise yields and reduce production costs. For current average short rotation cropping (SRC) production systems, Italian poplar shows the highest cost at 5.5 € GJ^{-1} followed by Swedish willow at 4.4 € GJ^{-1} and Brazilian eucalyptus is produced to the lowest costs at 2.8 € GJ^{-1}. It was assessed to what extent production costs can be reduced per step in the production cycle and how this affects the minimum cost levels that can ultimately be achieved. Ultimate cost reduction could lead to delivered costs of 2.2 € GJ^{-1} for poplar, 1.9 € GJ^{-1} for willow and 1.9 € GJ^{-1} for eucalyptus on better quality lands. Based on historic cost data and production trends, experience curves were applied providing progress ratios for poplar in Italy and eucalyptus in brazil. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The extent to, and rate at, which cost reductions can occur within the next 20 years were evaluated by combining current costs, minimum cost levels and progress ratios with ranges in European and global biomass demand projections. This shows that, at the assumed growth rates for biomass production in Europe and for global production, minimum cost levels can be reached within the next two decades.

Chapter 6 addressed research question 1 and 2 by modelling the diffusion of biomass-to-biofuel routes in the European biofuels market based on (relative) cost developments. Based on the technical biomass potentials assessed in chapter 2, the prospects for cost developments in cropping systems and conversion technologies and European biofuel demand projections, the (future) competition between biofuels was simulated. A sensitivity analysis evaluates the impact of variations in assumptions such as the 'timing of market introduction', 'investment costs' and 'sub-targets for diesel and gasoline' on the market diffusion patterns of different biofuel routes. Results show that 1st generation biodiesel is the most cost competitive current fuel, dominating the early market. With increasing demand, modestly productive oilseed crops become more expensive rapidly, due to restricted productivity, providing opportunities for advanced biofuels to enter the market. While biodiesel supply typically remains steady until 2030, a large share of additional demand is delivered by advanced biofuels, supplying up to 60% of total supply by 2030. Sensitivity analysis shows that (1) overall increasing investment costs favour biodiesel production, (2) separate gasoline and diesel sub-targets may diversify feedstock production and technology implementation, thus limiting the risk of failure and preventing lock-in and (3) the sooner advanced biofuels enter the market the larger are its chances to increase market share. Overall production costs for 1st and 2nd generation biofuels will, for most cases, be cost competitive with fossil transport fuels[3], in the range of 70–130 $ $barrel^{-1}$ (7.8–14.5 € GJ^{-1}) oil equivalent, by 2030. First generation biodiesel shows stable overall production costs at an equivalent of 100 $ $barrel^{-1}$. Advanced biofuel options start-off more expensive, in the range of 180 $ $barrel^{-1}$ (20 € GJ^{-1}), but have opportunities to reduce costs significantly, by 30–60%, to become cost competitive with fossil transport fuels in the range of 70–130 $ $barrel^{-1}$ (7.8–14.5 € GJ^{-1}) by 2030.

7.4 Methodological approaches, limitations and lessons

This thesis has deployed and improved a variety of methods and approaches that are common to energy and environmental system analysis. This section provides an overview how these methods were used including some limitations, lessons drawn and recommendations.

[3] An exchange rate of 1.4 US$ to the Euro was applied.

Chapter 2 deployed several methodological steps to assess Europe's techno-economic biomass potentials until 2030 by constructing spatially explicit **cost-supply curves** for energy crops in Europe. This required (1) an evaluation of the surplus land that can become available for energy crop production in Europe, (2) a spatially explicit energy crop yield estimation and (3) a cost assessment for these crops. To account for variations in yield growth rates, an essential but uncertain factor in the first step, a **scenario analysis** was deployed describing three storylines with different rationales on political, technological and economical developments. In particular, three land conversion scenarios were formulated that reflected different (agricultural) policy settings. Apart from changing efficiencies in agriculture, other issues that were considered included trends in nature conservation, organic farming and the use of pasture land. A key limitation to this approach is the focus on EU production only. Land potentials for bioenergy will also be affected by developments in global food commodity markets, and resulting changes in EU self-sufficiency in food and feed. This self-sufficiency has been assumed to remain constant in this study. Other approaches can verify this assumption, e.g. general equilibrium modeling of the global food system.

Chapter 3 further scrutinized past developments in European agriculture, in order to gain insights into the cause-and-effect relationship between driving forces in agriculture and resulting yield levels. To make this connection explicit, country **aggregated agricultural output and input trends** were combined with an overview of **driving forces** that steered the observed developments. This involved a narrative overview of factors that have steered agricultural developments in Europe over the last five decades. This was illustrated by a quantitative review of key developments in agriculture, viz. time-series for key inputs (labour, machinery, fertilizer and pesticides) and yields (wheat, rape seed, sugar beet and cattle) between 1961 and 2007 for the Netherlands, France, Poland and Ukraine. Quantitative and qualitative insights were combined to give an integrated picture of the aggregated input and output trend, key policies, economic developments and developments in rural Europe. Subsequently, temporal shifts within countries and differences between countries were identified and explained and, based on this, future productivity development trajectories were described. Methodologically, this is clearly a suboptimal approach, as there is no straightforward connection between the narrative description and the actual developments. However, it appeared to be the only feasible approach: A preliminary statistical **multi factor productivity (MFP) analysis**, connecting input and output variables, showed that such an analysis was not feasible given the multitude of causal factors, the entailing data requirements for the analysis and the limited data data, both in time period and in sectoral detail. Future endeavors may consider applying an MFP approach to parts of the subjects studied (e.g. sub-sectors in countries) which could quantitatively decompose productivity into its individual drivers and provide a comprehensive insight into the specific contribution of each production factor to agricultural productivity over time.

In chapter 4, the environmental implications were assessed that result from land conversion scenarios set out in chapter 2. An **environmental assessment** method (MITERRA-Europe model) was used that calculates nitrogen (N_2O, NH_3, NO_x and NO_3) and greenhouse gas (CO_2, CH_4 and N_2O) emissions, as well as soil organic carbon stock changes, using emission and leaching factors. The model is used to assess effects of land-use and management changes on nitrogen losses, and interactions between these variables on a regional level for Europe. Key limitation of this approach is its simplification of biochemical processes and generalization of highly diverse agricultural systems. Although these necessary simplifications of the model lead to loss of detail, its strength is that a uniform approach for all European countries enable a consistent and transparent assessment.

To explore future developments in the performance of global SRC systems, a main objective in chapter 5 was to evaluate the extent to which **experience curves** could be applied to **SRC biomass production systems**. Methodological challenges included data limitations, difficulties of comparing different crop types and the choice of the system boundaries, both in time and geographic scope. The found progress ratios and estimated minimum production cost indicate that considerable cost reduction are possible within the next 20 years. However, they should be considered first order estimates, given the data limitations. Also, a crucial prerequisite is that sufficient SRC is produced to gain sufficient experience and reach associated cost reductions. Several key areas for further study were identified, e.g. to get a better (and more quantitative) overall understanding of future learning potential of both perennial and annual crops. Next, a component experience curve could be applied to evaluate more in-depth which steps in the cropping system do and can contribute to cost reductions. Furthermore, the found progress ratio's for SRC systems could be deployed in energy scenario modelling, e.g. to assess the effect of policy interventions on the rate at which cost reduction are reached, also in relation to competing production systems.

In Chapter 6 the **diffusion of competing biomass-to-biofuel routes** in Europe was assessed. The deployed model (BioTrans) is designed to calculate least-cost supply chains to meet demand scenarios based on given demand projections, current and future feedstock and technology potentials and costs. To model technological progress, it was attempted to apply **experience curves** to conversion technologies. This required different approaches for first and second generation biofuel technologies. The most challenging task was to adequately model advanced biofuel options, because of the absence of (historic) production cost data related to installed capacity. This challenge was met by using both bottom–up engineering scaling data and top–down empirically derived progress ratios, which had to be corrected for scale effects. Sensitivity analyses on key parameters (e.g. progress ratios, scaling laws, time of market introduction etc.) allowed for an exploration of their impact on cost developments and - especially second generation biofuels - market introduction and diffusion patterns. However, the model could not address the competition dynamics for biomass and related land between the different applications for power and heat, transport fuel and biomaterials.

The combination of approaches delivered the most comprehensive insights. This includes the bottom-up insights gained for agricultural developments and the performance of cropping systems and (advanced) biofuel technologies including the application of experience curves. The combination of scenario analyses for production potentials, economic performance and environmental impact analysis has provided a much more coherent picture of possibilities, limitations, implications and preconditions for realizing sustainable biomass-supplies in Europe but further refinement is possible, particularly relevant and promising issues include: development of spatially explicit (GIS-based) and multi-sector modeling frameworks; models that are better equipped to assess the impacts of policy interventions and better and more case studies on cropping systems, technological performance, etc .

7.5 Main findings and conclusions

Based on the findings of chapters 2-6, the following answers to the three main questions can be given.

Research question 1: What is the techno-economical biomass production potential in Europe, how is it spatially distributed and what driving forces steer its development over time?

The ultimate technical European[4] biomass potential for energy crop production on European croplands amounts 1.6 to 14.1 EJ y^{-1} by 2030. This wide range is caused by differences between specific crops and by a number of assumptions discussed further below. Herbaceous grassy crops, produced on grasslands, could add an additional 4.3 EJ y^{-1}. Availability of these potentials is based on the assumption that over time croplands and grasslands become available for energy crop production as a result of productivity increases in food and livestock production. Towards 2030 surplus cropland in Europe can expand to 66 million hectares and surplus grassland to 24 million hectares. Grasslands should, however, be considered for perennial grass production only, to prevent GHG emissions when grassland would be converted. In addition to dedicated energy production, agricultural residues could add 3.1-3.9 EJ y^{-1} and forestry residues and forestry resources 1.4-5.4 EJ y^{-1}. The ultimate technical biomass potential from these sources combined, add up to a maximum of 27.7 EJ y^{-1} in Europe. To put this figure into perspective, between 2005 and 2010, Europe's total primary energy production from biomass increased by 53%, from 3.0 to 4.6 EJ y^{-1} and is expected to grow to 6.2 EJ y^{-1} by 2020. The associated production costs at which energy crops can be produced in Europe show large variation between regions. In general, significantly lower costs can be reached in the CEEC than in the WEC, the main reason being lower costs for land and labor in the CEEC. The majority of first generation energy crops are available at production costs of 5.0–15.0 € GJ^{-1} compared to 1.5-4.5 € GJ^{-1} for second generation energy crops. Cost differences can be attributed to the relatively extensive production practices and high yields for second generation feedstocks. The majority of agricultural residues can be made available at costs of 1.0-4.0 € GJ^{-1} and forestry residues at costs of 2.0-4.0 € GJ^{-1}.

The opportunities for energy crops to be produced (over time) are unevenly distributed within Europe, with the CEEC posing the more attractive region with relatively high potentials and low costs. Regions that stand out in this respect are large parts of Poland, the Baltic States, Romania, Bulgaria and Ukraine. In Western Europe, France, Spain and Italy are moderately attractive applying the low-cost high-potential criterion. While the

4 Europe here refers to the EU27, Norway, Switzerland and Ukraine.

higher potential in the CEEC may sustain over time, cost levels may not as economic growth in the CEEC proceed gradually converging living standards to WEC levels.

These findings were based on the assumption that cropland and grassland needs for future domestic food production decrease as productivities per hectare in crop and livestock production gradually increase, in line with historic trends. Croplands that are freed this way can be supplemented with agricultural lands that (already) lie fallow. Besides these supposed rises in agricultural productivities, two other key factors steer the extent and rate at which European biomass potentials can develop: the population, diet and aggregated food demand developments and the net trade balance of Europe's food and animal feed products. However, of these three driving forces, ongoing yield developments are identified as the most prominent factor to open up Europe's biomass potential.

To explore and verify at what rate and to what extent future yields may develop, under influence of economic, political and technological driving forces, an analysis of agricultural yield developments in the past five decades in Europe was made. Two observations stand out: Firstly, European yields have increased significantly over the last five decades. Historic developments in European crop and animal protein productivity between 1961 and 2007 show an mean annual growth rate of 1.6%. In relative terms, developments are slower on average in the Netherlands and France at 1.0% y–1 than in Poland and Ukraine (USSR) at 2.2% y^{-1}. In absolute figures, however, growth has been considerable in WEC and modest in the CEEC. As a consequence, the WEC have realized more of their agro-ecological potential compared to the CEEC which suggests a considerable potential for yield growth in the CEEC. Secondly, a clear correlation exists between achieved yield growth rates and the implemented agricultural policy at that time, both in periods of positive and negative yield growth. In periods and countries where stimulating policies (e.g. intervention prices) were implemented yields went up and reversely, in the absence or abolishment of stimulating policies yields contracted. Trend data show that significant yield changes can be realized over a short period of time. Outcomes hence suggest that productivity levels can be actively steered by policy and economic incentives rather than being just the result of autonomous developments such as economic growth.

Research question 2: To what extent can biomass potentials be realized sustainably in Europe without imposing adverse environmental impacts and conflicts with food production?

A main finding is that, in European agriculture, it is possible to combine large-scale biomass production with food production sustained at current levels, without direct or indirect land-use changes and while accomplishing significant net cumulative greenhouse gas (GHG) emission reductions when both bioenergy and agricultural production are considered. Raising agricultural output without the need to convert nature areas and grasslands into additional cropland is established by continuous yield increases. This rationalization, at growth rates in line with historic observations, within agro-ecological possibilities, can gradually reduce the land base that needs to be in cultivation for food production. Together with land that already lies fallow, this frees up cropland that would not be required for domestic food production by 2030.

However, as past experiences of agricultural intensification show, periods with considerable yield growth have not always coincided with periods of high resource use-efficiencies. For example, intervention prices have facilitated investments in intensification, especially fertilizers, leading to increasing yields but sometimes to lower output-per-input efficiencies because inputs were not used efficiently in the absence of an economic incentive. Examples of adverse effects to the (local) environment include acidification and eutrophication. To the other end, environmental legislation that was introduced in the late 1970s, mainly in the WEC, incentivized the more efficient use of (restricted) inputs. Effects were clearly shown to sustain productivity levels while being able to reduce input levels significantly. These mechanisms illustrate the importance of appropriate policy to stimulate productivity while safeguarding efficiency, minimizing environmental impacts, increase resource use efficiency and (related to this) sustainability.

The net GHG mitigation balance of EU agricultural land use in the period 2004-2030 was assessed for several land-use variants, specifying the emissions of nitrous oxide (N_2O), the net soil organic carbon (SOC) fluxes and the emissions abated by replacing fossil fuels for transport with biofuels. Maintaining the current agriculture results in 4.9 $GtCO_2$-eq. of cumulative N2O emissions by 2030. Intensified food production and energy crop production on freed cropland in combination with mitigation measures can significantly reduce cumulative emissions for annual crops. When oil, starch or and sugar crops are used as energy crop on this freed cropland, cumulative emissions of agricultural land use are reduced to 1.9, 1.5 and 2.1 $GtCO_2$-eq., respectively. When perennial crops are applied, cumulative emissions are more than outbalanced and agricultural land use becomes a net sink, with cumulative emission mitigations of 3.3 and 4.5 $GtCO_2$-eq., for grass and wood crops respectively. Nitrous oxide emissions will increase modestly due to higher fertilizer-application rates, though at improved efficiencies per unit crop quantity produced. Emission mitigation results partly from the temporary increase in SOC sequestration though mainly from replacement of fossil resources by biomass resources.

The actual GHG mitigation that can be realized in European agriculture critically depend on two preconditions that need to be met: Firstly, gradual intensification of food production can reduce net emissions. The increase in N_2O emissions due to higher fertilizer application on croplands used for food production can be compensated mainly by dedicating freed croplands to extensive production practices. Meeting this precondition avoids iLUC, because biomass production gradually expands in balance with improved agricultural management. Simulations confirm that the mitigation potential of biomass production on freed croplands is maximized when perennial grasses or woody crops are planted instead of annual crops. This is because perennials generally require less intensive management, have a higher fertilizer-use efficiency and generally have higher yields, both in terms of dry weight biomass and biofuel equivalents. Also, low(er) quality land is suited for perennials, which results in improved environmental performance (e.g. increases in carbon stocks and less leaching) compared to annual crop production on such soils. Secondly, the implementation of structural improvements to agricultural management should be an integral part of any effort to intensify agriculture and develop a biofuels strategy further. In this respect, three measures that can immediately be implemented and that were found to be effective include: reduced tillage, soil carbon enhancement and more efficient fertilization.

Research question 3: What are possible diffusion pathways of different competing biofuel production routes distinguished between feedstock and conversion, given their current and future economic performance?

The contribution of dedicated energy cropping to the overall biomass supply is expected to increase. Currently, mainly heat and power production use solid biofuels, but increasing competition can be expected from advanced biofuel production in the coming decade. Two factors play a key role in the competition between first and second generation biofuels: the build-up of their supply chain costs (particularly feedstock and conversion costs), and the prospects for these cost items to decrease in the course of deployment. In this context, it should be realized that first generation biofuels have higher feedstock costs and lower conversion costs, while second generation biofuels have lower feedstock costs and higher conversion costs. The consequence of this is that first generation biofuels depend especially on progress in feedstock costs while second generation biofuels depend to a larger extent on cost reduction in conversion technologies.

Based on the current economic performance of feedstocks and conversion technologies and their future prospects, simulations can provide insight into how the relative diffusion of biofuel-routes can develop over time. In addition, the influence of some exogenous market developments (e.g. higher raw material prices) and policy choices (e.g. separate bio-diesel and bio-ethanol targets) were evaluated. Some observations are discussed. Firstly, second generation biofuels are likely to surpass first generation biofuels in production costs somewhere in the next two decades. Especially when ambitious policy targets drive-up demand for feedstocks, second generation biofuels can enter the market, start up-scaling and gain operational experience, steadily decreasing production costs. This illustrates the crucial prerequisite that market access is needed to gain experience and reduce costs. Second generation biofuels may also compete against each other. As both options are still emerging, the timing of market entrance is crucial. Reasoning along the lines of the experience curve hypothesis: when a technology starts producing, it gains operational experience thereby reducing its production costs which gives it a cost-advantage. Consequently, when the period between the market entrance of two competing technologies extends, the commercial chances for the last one to enter the market shrink. This advocates the adoption of a portfolio approach to prevent lock-in of (potentially sub-optimal) technologies in early phases of market development. One specific policy measure for biofuels that could stimulate portfolio creation is a differentiated biofuel targets for gasoline and diesel substitutes. Secondly, when capital costs for conversion technologies would rise proportionally for all technologies, for example as a result of increased raw material prices (e.g. for steel or concrete), this would give first generation biofuel-routes a comparative advantage over second generation biofuel-routes. This could delay the market entrance or further diffusion of advanced biofuels by several years up to a decade. Reversely, lower raw material prices would stimulate second generation biofuels.

A prerequisite, however, for up-scaling and establishment of a sizeable second generation biofuels industry is the availability of a stable and sufficiently large resource base of lignocelluloses feedstocks. In achieving that, the power and heat sector may play a crucial role in the capacity building of this lignocelluloses resource base because power and heat production based on solid biofuels for various routes (not all) is already cost-competitive today. To expand the lignocellulosic resource base beyond residues and wastes, SRC forms a particular interesting feedstock category, that is optimized for fast growth and high yields. While SRC is produced in different settings around the globe, in this thesis the economic performance and prospects for improvement were assessed for poplar in Italy, willow in Sweden and eucalyptus in Brazil. Current average production costs for short rotation crops are highest for poplar (5.5 € GJ-1), followed by willow (4.4 € GJ-1) and eucalyptus (2.8 € GJ-1). Bottom-up cost analysis, assessing the full improvement potential on productive soils, reached minimum cost levels in the order of 2 € GJ-1 for all three crops. Past cost developments indicate that per hectare cultivation costs have decreased by roughly two-thirds in recent decades for poplar in Italy and eucalyptus in Brazil. For Sweden, due to the limited volumes produced, no overall cost decline was observed over the two decades that willow is produced. Yield increases have been the most important driving force behind production cost declines. Yields were augmented through implementation of improved breeds and clonal varieties, increased fertilization levels, better pest control, ongoing mechanization in planting, tillage and harvesting and efficiency gains in local transport.

Based on these limited historic yield and cost data calculated progress ratios are crude. Brazilian eucalyptus production follows a steeper slope (63–73%) than poplar in Italy (71–78%). The progress ratios found for eucalyptus and poplar fall within the broad range (55–80%) that was already found for annual crops. On average, it appears that PRs for the production of annual and perennial crops seem to be on the low side, i.e. cost reduction occurs faster compared to other energy supply technologies that display a mean progress ratio of 84% (Junginger et al., 2010). The found progress ratios were combined with European and global primary biomass demand projections to assess how fast the identified minimum cost level of 2 € GJ-1 can be reached. Outcomes suggest that when European biomass ambitions are increasingly met by European SRC production, learning induced cost reductions can be achieved fairly rapidly, reaching minimum cost levels of 2 € GJ-1 for poplar and willow between 2022-27. For eucalyptus production, considering its substantial production thus far, absolute cost reductions are reached at a slower pace, and minimum cost levels are expected to be reached between 2021-2030.

7.6 Recommendations for policy and further research

Based on these findings, recommendations for policy and further research are identified.

Policy recommendations:

- The European Commission should develop an integrated vision on the policy domains of agricultural development and renewable energy. A (partial) alignment or integration of the common agricultural policy (CAP) and the renewable energy directive (RED) could provide clear benefits. For example, investments in improved agricultural management, e.g. to comply with the CAP's cross-compliance standards, can at the same time cause substantial GHG mitigations. Through improved agricultural efficiencies, cropland can be released that may be used for energy crop production to produce biofuels. The consequent replacement of fossil transport fuels and associated GHG mitigation benefits can potentially also deliver financial benefits, e.g. under the emission trading scheme (ETS).

- Sustainability frameworks can be improved, based on insights from this thesis, with clear guidelines on expanding biomass production (in Europe) with sustainable rationalisation and improved agricultural efficiencies. Such a strategy can help avoiding iLUC, while biomass production gradually expands in balance with improved agricultural management. This can lead to overall better environmental performance of agriculture and create new economic opportunities. In other words, it would lead to synergy between bioenergy and agriculture instead of conflict.
- Energy crop cultivation, in particular perennial short rotation crops, requires capacity building to scale-up production and gain experience in different settings. Stable and coordinated policies on an EU level should be provided. Stable policies (for periods of a decade at a minimum) prove necessary to develop a competitive industry.
- Dedicated feedstock and (advanced) biofuels production can become cost-competitive soon. Learning-investments in advanced biofuel technologies could facilitate their market entrance and speed-up diffusion in the market. In parallel, investments in SRC production may concentrate a larger share of this production in Europe and reap (potentially substantial) benefits in the near future. This would require dedicated and harmonized EU-wide policy to realize both the required production of lignocellulose crops and the commercialisation of advanced biofuel technologies – which is not yet foreseen in (many of) the national renewable action plans (NREAPs). Under such a scenario, the use of more land efficient lignocellulosic resources would increase, which would potentially curb more GHG emissions than when fossil fuels for transport are replaced by first generation biofuels.

<u>Recommendations for further research:</u>

- To further underpin policy strategies as discussed above, a thorough quantification of learning investments, environmental, social and macro-economic costs and benefits is desired. This could then be compared to an alternative scenario with increasing imports of biomass from outside the EU.
- Although bioenergy production can have environmental benefits, the impacts on (agro-) biodiversity and water stress are still poorly understood and require further research.
- Further investigation of developments in crop cultivation is needed, both annual crops and perennial short rotation crops, to gain better overall understanding of their future learning potential and opportunities to reduce costs.
- Future endeavors may consider applying an multi factor productivity (MFP) approach to parts of the agricultural production system (e.g. sub-sectors in countries) which could quantitatively decompose agricultural productivity into its individual drivers and provide a comprehensive insight into the specific contribution of each production factor to agricultural productivity over time.
- Further refinement is possible on (modeling and) understanding the spatial dynamics of changing land uses in relation to large-scale biomass use in different sectors.

Spatially explicit (GIS-based) and multi-sector modeling frameworks could develop new insights on these issues.

- Dynamics of developments in Europe's food (and feed) self-sufficiency (e.g. in relation to global food commodity markets) can be explored for example through general equilibrium modeling of the global food system.

Samenvatting en conclusies

Bio-energie in Europa en cruciale aspecten voor expansie

Fossiele grondstoffen domineren de wereldwijde energiehuishouding. Zij worden gebruikt voor de productie van transportbrandstoffen, warmte en kracht en als een grondstof voor plastics, chemicaliën en kunstmest. Door de eindigheid van fossiele bronnen is deze afhankelijkheid op de lange termijn niet duurzaam. Voorts heeft de substantiële toename in het gebruik van fossiele bronnen geleid tot verhoogde antropogene emissies van koolstofdioxide. Als gevolg hiervan zijn atmosferische broeikasgasconcentraties toegenomen met gevolgen voor het klimaat. Broeikasgassen komen vrij bij verbranding van koolwaterstoffen, ontbossing, veeteelt en (kunst)mestgebruik. Energiegerelateerde broeikasgasemissies zijn onder andere te reduceren door het gebruik van bio-energie. Bio-energie verwijst naar een verscheidenheid aan bronnen en technologieën gebaseerd op biomassa. Bronnen van biomassa zijn onder meer residuen afkomstig van de land- en bosbouw, een- of meerjarige energiegewassen en diverse andere biomassa reststromen. Bio-energie technologieën produceren direct elektriciteit of warmte of gasvormige, vloeibare of vaste biobrandstoffen.

Zowel wereldwijd als in Europa groeit het gebruik van (primaire) biomassa voor energie. In Europa kan dit vooral worden toegeschreven aan energie- en klimaatdoelstellingen, inclusief specifiek biobrandstoffenbeleid. De toename van het gebruik is toe te schrijven aan de diverse voordelen van bio-energie. Ten eerste kan bio-energie fossiele brandstoffen vervangen, waaronder aardolie, de meest schaarss fossiele energiebron. Ten tweede reduceert bio-energie broeikasgasemissies, mits de productieketen duurzaam is. Ten derde kan biomassa worden geïntegreerd in de meeste bestaande energie-infrastructuren. Zo kunnen biobrandstoffen benzine en diesel en dus aardolie direct vervangen. Daartegenover staat dat door de recente toename van modern bio-energiegebruik diverse risico's aan het licht zijn gekomen. Zo kan productie van bio-energie leiden tot onder andere veranderingen in landgebruik en ontbossing met mogelijk negatieve ecologische effecten. Verder kan er competitie ontstaan tussen bio-energie- en voedseltoepassingen om grondstoffen en landbouwgrond, met ongewenste effecten tot gevolg.

Europa speelt een belangrijke rol in de (verdere) ontwikkeling van bio-energie, met een ambitieus beleid voor duurzame energie en een sterk ontwikkelde en technologisch vooraanstaande agrarische sector. De landbouwproductiviteit is significant verbeterd als gevolg van een sterk gemeenschappelijk landbouwbeleid (Common Agricultural Policy, CAP[5]) de afgelopen decennia. De Europese Commissie ziet in haar energie- en klimaatdoelstellingen tot 2020 en daarna een grote rol weggelegd voor bio-energie. Om de mogelijkheden, beperkingen en implicaties van een toename van bio-energie in de Europese context te evalueren dienen diverse cruciale aspecten diepgaand en in samenhang te worden onderzocht:

[5] In deze Nederlandse samenvatting worden Engelse acroniemen gebruikt om ze consistent te houden met de hoofdstukken in het proefschrift.

- Verdere analyse van de voornaamste sturende factoren die van invloed zijn op toekomstige biomassapotentiëlen en de geografische spreiding hiervan over de Europese regio's.
- De mate waarin agrarische opbrengsten kunnen worden verhoogd, en de snelheid waarmee dit kan gebeuren. Dit is een van de belangrijkste punten in het debat over bio-energie potentiëlen.
- Voorts is een integrale evaluatie nodig van specifieke milieu-impacts als gevolg van toegenomen bio-energieproductie en verdere rationalisatie van de agrarische sector.
- Om de huidige en toekomstige economische prestaties van bio-energie opties te evalueren is verder onderzoek nodig naar de perspectieven voor het reduceren van kosten van productiesystemen voor meerjarige energiegewassen, en van (geavanceerde) bio-energie conversietechnologieën. Dit vooral gezien de verwachte rol die meerjarige gewassen en geavanceerde conversie-opties gaan spelen en tegelijkertijd de beperkte huidige ervaring op dit gebied.
- Gerelateerd aan de mogelijkheden om de economische prestatie te verbeteren is het van belang de interacties tussen concurrerende duurzame en fossiele technologieën te modelleren om inzicht te krijgen in de mogelijke diffusiepatronen van deze technologieën.

Doel en onderzoeksvragen

Doel van dit proefschrift is het evalueren van ontwikkelingspaden voor bio-energie in Europa op basis van een analyse van de voorwaarden die nodig zijn voor verdere ontwikkeling, een economische vooruitblik op zulke ontwikkelingen en een analyse van de effecten op het milieu. Drie hoofdvragen (V1-V3) adresseren de beschreven kennislacunes zoals beschreven in het eerste hoofdstuk van deze samenvatting.

1. Wat is het techno-economische potentieel van biomassaproductie in Europa, hoe is dit geografisch verdeeld en wat zijn de voornaamste sturende factoren in de ontwikkeling ervan over de tijd?
2. In welke mate kunnen biomassapotentiëlen in Europa duurzaam worden gerealiseerd zonder negatieve effecten op het milieu of conflicten met voedselproductie te veroorzaken?
3. Wat zijn mogelijke diffusiepaden van verschillende concurrerende biobrandstofroutes uitgesplitst naar ontwikkelingen in biomassa-grondstofproductie en conversietechnologieën, gegeven hun huidige en toekomstige economische prestaties?

	V1	V2	V3
Hoofdstuk 2: Biomass resource potential and costs	•	•	•
Hoofdstuk 3: Productivity developments in European agriculture	•	•	
Hoofdstuk 4: Environmental impacts of integrating biomass production into European agriculture		•	
Hoofdstuk 5: Learning in dedicated wood production systems			•
Hoofdstuk 6: Competition between biofuels	•		•

Samenvatting van de resultaten

Hoofdstuk 2 gaat in op de onderzoeksvragen 1, 2 en 3 met een analyse van het Europese productiepotentieel voor biomassa-grondstoffen en de kosten hiervan. Drie scenario's zijn ontwikkeld met verschillende groeisnelheden in gewasopbrengsten en efficiëntie van de veeteelt. Resultaten laten zien dat het maximale areaal aan land voor de productie van bio-energiegewassen – wanneer de vraag naar land voor voedsel en andere functies eerst wordt gedekt – 90 miljoen hectare zou kunnen bedragen in 2030; 66 miljoen hectare landbouwgrond en 24 miljoen hectare grasland. Het potentieel aan primaire biomassa uit energiegewassen varieert tussen de 1.7 en 12.8 EJ y^{-1}, afhankelijk van het energiegewas dat wordt gebruikt en het scenario. Residuen uit land- en bosbouw kunnen aan dit potentieel biomassa respectievelijk 3.1–3.9 en 1.4–5.4 EJ y^{-1} toevoegen. Wat betreft de productiekosten, voor eerste generatie biobrandstoffen kunnen grondstoffen (zoals koolzaad, granen en suikerbiet) worden geproduceerd voor 5–15 € GJ^{-1} vergeleken met 1.5–4.5 € GJ^{-1} voor tweede generatie gewassen zoals snelgroeiende grassen en houtsoorten. Kosten voor reststromen uit de landbouw tussen 1 en 7 € GJ^{-1} en bosbouwresiduen tussen 2 en 4 € GJ^{-1}. Er zijn grote verschillen tussen Europese regio's wat betreft productiepotentiëlen en kosten van biomassa. Regio's die opvallen door een hoog productiepotentieel en lage kosten zijn grote delen van Polen, de Baltische staten, Roemenië, Bulgarije en Oekraïne. In West Europa zijn Frankrijk, Spanje en Italië gemeten naar deze criteria interessant.

Vanwege de cruciale rol die ontwikkelingen in de landbouwproductiviteit spelen bij het realiseren van het productiepotentieel aan biomassa is dit onderwerp in meer detail geanalyseerd in **Hoofdstuk 3** (ingaand op onderzoeksvragen 1 en 2). Dit hoofdstuk gaat in op de vraag of, hoe snel en in welke mate maximale gewasopbrengsten kunnen worden gerealiseerd in Europa in de komende decennia. Historische ontwikkelingen in de Europese gewasproductiviteit en productie van dierlijk eiwit tussen 1961 en 2007 laten een gemiddelde jaarlijkse groeisnelheid zien van 1.6%. Deze groei is relatief gezien gemiddeld langzamer in Nederland en Frankrijk met 1.0 % y^{-1} in vergelijking met Polen en Oekraïne (USSR) met 2.2 % y^{-1}. In absolute zin is de groei echter aanzienlijk geweest in West Europa en bescheiden in Centraal en Oost Europese landen. Trends in opbrengsten laten verder zien dat significante opbrengstveranderingen kunnen worden gerealiseerd in korte perioden. In sommige decennia zijn groeisnelheden van 3–5% y^{-1} behaald in diverse landen voor verschillende gewassen . In Oost-Europese landen, zijn tijdens de politieke transitieperiode begin jaren negentig echter ook negatieve groeicijfers geobserveerd van -7% y^{-1}.

Hoofdstuk 4 adresseert onderzoeksvraag 2 middels een evaluatie van de milieu-impacts die samenhangen met een uitbreiding van productie van energiegewassen op Europese landbouwgronden. De simulaties beschrijven vier belangrijke ontwikkelingen die van invloed zijn op de (netto) broeikasgas emissies van het Europese landgebruik. De beschreven ontwikkelingen zijn: (1) Een geleidelijke intensivering van de agrarische productie, (2) implementatie van structurele verbeteringen in land management, (3) geleidelijke uitbreiding van energie gewasproductie op gronden die niet meer nodig zijn voor voedselproductie, en (4) mitigatie van emissies door vervanging van fossiele brandstof in de transportsector door de geproduceerde biobrandstoffen. Continuering van de agrarische productie op de huidige niveaus resulteert in cumulatieve emissies uit landgebruik ter grootte van 4.9 $GtCO_2$-eq. tot 2030. Een combinatie van geïntensiveerde voedselproductie, gecombineerd met productie van energiegewassen op vrijgekomen gronden en implementatie van mitigatiemaatregelen kan deze cumulatieve emissies significant reduceren. Wanneer olie-, zetmeel- en suikergewassen worden geproduceerd als energiegewassen op vrijgekomen gronden dan kan dit de cumulatieve emissies reduceren tot respectievelijk 1.9, 1.5 en 2.1 $GtCO_2$-eq. Wanneer meerjarige gewassen worden geproduceerd dan worden cumulatieve emissies meer dan gecompenseerd en legt het landgebruik in Europa netto koolstof vast, met cumulatieve emissiemitigatie van 3.3 en 4.5 $GtCO_2$-eq. voor respectievelijk grassen en bomen.

Hoofdstuk 5 gaat in op onderzoeksvraag 3 en analyseert het verbeterpotentieel in het verhogen van opbrengsten en het reduceren van kosten in de productie van energiegewassen. Van de huidige teeltsystemen met korte rotaties is de productie van Italiaanse populier het duurst (5.5 € GJ^{-1}), gevolgd door wilg in Zweden (4.4 € GJ^{-1}) en eucalyptus in Brazilië (2.8 € GJ^{-1}). Verder geeft de analyse inzicht in de mate waarin kosten kunnen worden gereduceerd per onderdeel van het teeltsysteem en hoe dit de mogelijke uiteindelijke ondergrens van de totale productiekosten beïnvloedt. Deze minimale productiekosten op goede gronden liggen voor populier op 2.2 € GJ^{-1}, voor wilg op 1.9 € GJ^{-1} en voor eucalyptus op 1.9 € GJ^{-1}. Verder is op het historische verloop van de productiekosten en productiehoeveelheden een leercurvebenadering toegepast waaruit leersnelheden (progress ratios, PRs) zijn afgeleid voor productie van populier in Italië en van eucalyptus in Brazilië. Deze analyse laat zien dat de productie van eucalyptus in Brazilië historisch gezien sneller heeft geleerd (63-73%) dan die van populier in Italië (71-78%). Op basis van deze PRs is een inschatting gemaakt van de snelheid waarmee kosten kunnen worden gereduceerd in de periode tot 2030. Hiertoe zijn de PRs gekoppeld aan huidige kostenniveaus van biomassa en Europese en wereldwijde vraagprojecties (top down). Uitkomsten laten zien dat, onder de aangenomen groeisnelheden van de Europese en wereldwijde biomassaproductie, minimale kostenniveaus kunnen worden bereikt in de komende twee decennia.

Hoofdstuk 6 gaat in op onderzoeksvragen 1 en 2 door het modelleren van de diffusie van conversieroutes van biomassa naar brandstof op de Europese biobrandstoffenmarkt, gebaseerd op (relatieve) onderlinge ontwikkelingen in productiekosten. De (toekomstige) competitie tussen biobrandstoffen is gesimuleerd uitgaande van de biomassa productiepotentiëlen uit hoofdstuk 2, Europese biobrandstof vraagprojecties, en de vooruitzichten voor kostenontwikkelingen in teeltsystemen en conversietechnologieën. In een gevoeligheidsanalyse is de impact geëvalueerd van variaties in bepaalde aannames – zoals 'het moment van marktintroductie', 'investeringskosten' en 'gescheiden doelstellingen voor diesel- en benzinevervangers' – op marktontwikkelingen van verschillende biobrandstofroutes. Resultaten laten zien dat 1^{e} generatie biodiesel de meest kosten-competitieve huidige biobrandstof is waardoor deze optie de markt in een vroeg stadium domineert. Met een toenemende vraag naar biobrandstoffen worden de matig productieve oliehoudende gewassen snel duurder waardoor geavanceerde biobrandstoffen de kans krijgen om de markt te betreden. Waar het aanbod aan biodiesel daarna redelijk constant blijft tot 2030 wordt de verdere toename van de vraag voor een groot gedeelte ingevuld door geavanceerde biobrandstoffen, tot circa 60% van de totale markt in 2030. De gevoeligheidsanalyse laat zien dat (1) hogere investeringkosten leiden tot een groter aandeel biodiesel, (2) separate doelstellingen voor het vervangen van diesel en benzine leiden tot meer diversificatie, zowel wat betreft de biomassa grondstoffenproductie als de technologische conversieroutes, waardoor het risico van falen en *lock-in* wordt verkleind en (3) hoe eerder geavanceerde biobrandstoffen op de markt worden geïntroduceerd hoe groter de kans is dat zij een groot marktaandeel verwerven. Productiekosten van zowel 1^{e} als 2^{e} generatie biobrandstoffen zullen, in de meeste gevallen, concurreren met fossiele transportbrandstoffen bij een olieprijs van 70-130 $ per vat olie equivalent (7.8–14.5 € GJ^{-1}) in 2030. Gemiddelde kosten van eerste generatie biodiesel zullen grotendeels gelijk blijven rond de 100 $ per vat. Geavanceerde biobrandstoffen daarentegen zullen in eerste instantie duurder zijn, beginnend rond de 180 $ per vat (20 € GJ^{-1}), maar deze brandstofroutes hebben de mogelijkheid om productiekosten significant te reduceren, met 30-60%, waardoor ze concurrerend kunnen worden bij een olieprijs van 70-130 $ per vat in 2030.

Methodologische benaderingen, beperkingen en lessen

Dit proefschrift heeft een aantal methodes en benaderingen toegepast en verbeterd die worden gebruikt in energie- en milieusysteemanalyses. Deze sectie biedt een overzicht van hoe deze methoden zijn toegepast. Verder worden de beperkingen en methodologische lessen bediscussieerd en aanbevelingen geformuleerd.

In hoofdstuk 2 zijn drie methodologische stappen toegepast om te komen tot een inschatting van Europa's techno-economische biomassapotentieel tot 2030. Het resultaat hiervan zijn (**kosten-)aanbodcurven** voor energiegewassen in Europa. Dit vereist: (1) een evaluatie van het surplus aan land dat beschikbaar kan komen voor productie van energiegewassen in Europa, (2) een ruimtelijk expliciete opbrengstinschatting en (3) een kostenanalyse voor deze energiegewassen. Om onzekerheden in toekomstige opbrengstontwikkelingen mee te nemen, een essentiële maar onzekere factor in de eerste stap, is een **scenarioanalyse** toegepast. Deze scenario's beschrijven verschillende verhaallijnen met betrekking tot politieke, technologische en economische ontwikkelingen. De scenario's hebben vooral betrekking op verschillende landgebruikveranderingen onder invloed van verschillende condities qua landbouwbeleid. Naast de in de scenario's meegenomen veranderingen in opbrengstniveaus zijn ook ontwikkelingen en randvoorwaarden in natuurbehoud, biologische landbouw en het gebruik van grasland meegenomen. Een beperking van deze aanpak is dat deze zich tot Europa beperkt. Terwijl het land dat beschikbaar kan komen ook afhangt van ontwikkelingen in de wereldwijde voedselgrondstoffenmarkt en mogelijke veranderingen in de zelfvoorzienigheid van Europa waar het gaat om voedsel en diervoeders.

In Hoofdstuk 3 zijn ontwikkelingen in de Europese landbouw in meer detail geanalyseerd, vooral gericht op het verwerven van een beter inzicht in de oorzaak-gevolgrelatie tussen belangrijke gebeurtenissen en sturende factoren in de landbouwsector en de invloed hiervan op opbrengstniveaus. Om deze relatie expliciet te maken is een gecombineerd overzicht geconstrueerd van **kwantitatieve geaggregeerde ontwikkelingen van agrarische *inputs* en *outputs*** en de belangrijkste **sturende factoren** die voor de geobserveerde ontwikkelingen verantwoordelijk zijn. Onderdeel hiervan was een beschrijvend overzicht van factoren die van invloed zijn geweest op ontwikkelingen in de Europese landbouw in de laatste vijf decennia. Het kwantitatieve overzicht bestond uit een overzicht van historische tijdreeksen voor de voornaamste *inputs* (arbeid, landbouwmachines, (kunst)mest en pesticiden) en opbrengstniveaus (van tarwe, koolzaad, suikerbieten en rundvee) tussen 1961 en 2007 voor Nederland, Frankrijk, Polen en Oekraïne. De kwantitatieve en kwalitatieve analyses zijn gecombineerd om een samenhangend beeld te schetsen van de geaggregeerde input en output ontwikkelingen, de belangrijkste beleidsmaatregelen, economische ontwikkelingen en ontwikkelingen in Europa's agrarische en landelijke gebieden. Voorts worden aan de hand van voornoemd overzicht verschuivingen over de tijd binnen landen en tussen landen geïdentificeerd en besproken. Op basis hiervan worden toekomstige ontwikkelingstrajecten beschreven. Vanuit methodologisch oogpunt is dit een suboptimale aanpak aangezien er geen directe relatie is te leggen tussen de beschrijvende analyse en de invloed van de beschreven sturende factoren en de bereikte opbrengstniveaus. Niettemin bleek deze aanpak de enig uitvoerbare, gelet op de brede geografische scope en de tijdsperiode van de analyse. Een verkennende statistische multi-factor productiviteit (MFP) analyse bleek niet mogelijk door de veelheid aan causale verbanden en een gebrek aan de benodigde data wat betreft de perioden en de sectoren waarvoor data nodig zouden zijn. Bij toekomstige onderzoeksactiviteiten zou een MFP-aanpak kunnen worden overwogen op bepaalde deelgebieden – zoals een sub-sector in een bepaald land. Een MFP-aanpak heeft het voordeel dat het geaggregeerde trends de kwantitatieve bijdrage van verschillende onderliggende factoren kan identificeren. Hiermee biedt deze aanpak de mogelijkheid een meer omvattend en specifieker beeld te vormen van welke factoren in welke mate aan een toename van de agrarische opbrengsten per eenheid land hebben bijgedragen.

Hoofdstuk 4 beschrijft een analyse van de implicaties voor het milieu als gevolg van de landgebruikveranderingen zoals beschreven in hoofdstuk 2. Voor deze **milieueffectanalyse** is gebruik gemaakt van het MITERRA-Europe model dat stikstof- en broeikasgasemissies berekent en veranderingen in de hoeveelheid bodemorganische koolstof, gebruik makend van emissie- en uitspoelingfactoren. Het model wordt toegepast voor het berekenen van de effecten van veranderingen in landgebruik en agrarisch management op stikstofverliezen en interacties tussen deze variabelen op een regionaal niveau in Europa. Belangrijkste beperkingen van deze aanpak zijn de versimpeling van biochemische processen en generalisatie van zeer diverse agrarische systemen. Hoewel deze modelsimplificaties het detailniveau van de uitkomsten beperkt, is de kracht ervan dat de uniforme aanpak toelaat voor heel Europa tot consistente en transparante resultaten te komen.

Om toekomstige wereldwijde ontwikkelingen te verkennen van korte gewasrotatie (Short Rotation Crop, SRC) productiesystemen omvat hoofdstuk 5 een analyse waarin een **leercurvebenadering** kan worden toegepast op **SRC productie systemen**. Methodologische uitdagingen bestonden onder andere uit een beperkte data beschikbaarheid, de beperkte mogelijkheid om gewastypen onderling te vergelijken en de keuze voor systeemgrenzen met betrekking tot de geografische en tijdsafbakening. De gevonden leersnelheden en geschatte minimale productiekosten laten zien dat het realiseren van substantiële kostenreducties mogelijk is tot aan 2030. Deze schattingen moeten echter voorzichtig gebruikt worden, zeker gezien de beperkte data waarop de analyse is gebaseerd. Een belangrijke voorwaarde om minimale kostenniveaus te behalen is dat er voldoende geproduceerd wordt om ervaring op te doen en zodoende kostenreducties te behalen. Relevante gebieden voor toekomstig onderzoek zijn geïdentificeerd, voor het verkrijgen van beter (en meer kwantitatief) inzicht van het toekomstig leerpotentieel van zowel meerjarige als eenjarige gewassen. Daarnaast zou een component leercurvebenadering kunnen worden toegepast om gedetailleerd te analyseren welke stappen in het gewas teeltsysteem kunnen (en waarschijnlijk zullen) bijdragen aan kostenreducties. Voorts kunnen de gevonden leersnelheden voor de SRC productiesystemen worden toegepast in energiemodellen (o.a. als onderdeel van scenario's) bijvoorbeeld om inzicht te krijgen in de rol die beleidsinterventies kunnen spelen in de snelheid waarmee kosten kunnen worden gereduceerd ook in relatie tot concurrerende technologieën.

In hoofdstuk 6 is de **diffusie van concurrerende biobrandstofroutes** geanalyseerd. Het voor de analyse gebruikte model (BioTrans) is ontworpen om met combinaties van (concurrerende) biobrandstof aanvoerketens een bepaalde biobrandstoffenvraag in te vullen tegen de laagst mogelijke kosten. De belangrijkste model-inputs zijn biobrandstof vraagprojecties, de biomassagrondstof aanbodcurven (zie hoofdstuk 2) en de verwachte kostendalingen van conversietechnologieën. Om technologische vooruitgang te modeleren is getracht leercurven toe te passen op de kosten van conversietechnologieën. Dit vereiste een verschillende aanpak voor eerste dan voor tweede generatie biobrandstoftechnologieën. De grootste uitdaging lag in het adequaat modeleren van de geavanceerde technologieën, vooral vanwege de beperkte beschikbaarheid van historische kostendata en hieraan gerelateerd de geïnstalleerde productiecapaciteit. Een oplossing hiervoor is gevonden in het combineren van *bottom-up* technologische data en *top-down* empirisch afgeleide leersnelheden, die voor schaaleffecten zijn gecorrigeerd. Een gevoeligheidsanalyse van de belangrijkste variabelen (zoals leersnelheden, opschalingsnelheden, het moment van technologische marktintroductie, *etc.*) maakte het mogelijk voor het inschatten van de impact van de gevarieerde waarden voor de cruciale variabelen op de diffusiepatronen van de verschillende biobrandstofroutes in te schatten. Wat het model echter niet kon – en waar in het onderzoeksveld momenteel behoefte aan is – is het modeleren van de onderlinge concurrentie om biomassa grondstoffen en land tussen andere biomassatoepassingen zoals voor warmte- en krachtproductie en biomaterialen.

Het combineren van de gebruikte methoden heeft de meest belangrijke inzichten opgeleverd. Zoals *bottom-up* inzichten in historische ontwikkelingen in de agrarische sector, de prestatie van gewasproductiesystemen en (geavanceerde) biobrandstoftechnologieën, inclusief het toepassen van een leercurvebenadering. De combinatie van een scenario analyse met betrekking tot productie potentiëlen, economische prestaties en de milieu impact analyses heeft een coherenter inzicht opgeleverd van de mogelijkheden, beperkingen, implicaties en voorwaarden voor het realiseren van een duurzaam biomassa-aanbod in Europa. Echter, verdere verbetering is mogelijk. Een relevante en veelbelovende mogelijkheid in dit kader is het verder ontwikkelen van (GIS gebaseerde) en multi-sectorale modellen die beter geëquipeerd zijn om te analyseren wat de impacts zijn van beleidsinterventies. Verder kan het uitvoeren van meer casestudies met een groter detailniveau het begrip van regionale mogelijkheden en beperkingen beter inzichtelijk maken.

Bevindingen en conclusies

Gebaseerd op de bevindingen in de hoofdstukken 2 tot en met 6 kunnen de volgende antwoorden op de onderzoeksvragen worden geformuleerd.

Onderzoeksvraag 1: Wat is het techno-economische potentieel van biomassaproductie in Europa, hoe is dit geografisch verdeeld en wat zijn de voornaamste sturende factoren in de ontwikkeling ervan over de tijd?

Het maximale Europese biomassapotentieel afkomstig van energiegewasproductie op Europese landbouwgronden bedraagt 1.6 tot 14.1 EJ y^{-1} in 2030. De grote spreiding in dit potentieel wordt veroorzaakt door verschillen in opbrengsten tussen specifieke gewassen en een aantal aannames die verderop worden besproken. Grasachtige gewassen, geproduceerd op huidig grasland, kunnen een extra potentieel van 4.3 EJ y^{-1} toevoegen. Deze potentiëlen gaan uit van de veronderstelling dat over de tijd landbouwgrond en grasland beschikbaar kunnen worden gemaakt zonder andere functies in het gedrang te brengen door het verhogen van opbrengsten per eenheid land voor voedselgewas- en veeproductie. Richting 2030 kan het landbouwareaal dat niet benodigd is voor voedselproductie groeien tot 66 miljoen hectare en 24 miljoen hectare grasland. Grasland echter kan alleen in aanmerking worden genomen voor de productie van meerjarige grassen, om te voorkomen dat er netto meer broeikasgassen worden geëmitteerd door een conversie van gras- naar landbouwgrond. Naast energiegewasproductie kunnen agrarische residuen 3.1-3.9 EJ y^{-1} en bosbouwresiduen en houtproductie 1.4–5.4 EJ y^{-1} toevoegen. Het maximale technische biomassapotentieel van al deze bronnen gecombineerd in Europa bedraagt 27.7 EJ y^{-1} in 2030. Om dit getal in perspectief te plaatsen; tussen 2005 en 2010 nam de (primaire) biomassaproductie in Europa toe met 53%, van 3.0 naar 4.6 EJ y^{-1} en de verwachting is dat deze productie verder toe zal nemen tot 6.2 EJ y^{-1} in 2020. De kosten waartegen deze verschillende biomassagrondstoffen kunnen worden geproduceerd variëren sterk tussen Europese regio's. Over het algemeen zijn de kosten in Centraal en Oost Europese landen (*Central and Eastern European Countries*, CEEC) significant lager dan in West Europese landen (*Western European Countries*, WEC). De voornaamste redenen hiervoor zijn lagere kosten voor land en arbeid in de CEEC. Het grootste gedeelte van de eerste generatie energiegewassen kunnen worden geproduceerd voor 5–15 € GJ^{-1} vergeleken met 1.5–4.5 € GJ^{-1} voor tweede generatie energiegewassen. Kostenverschillen kunnen worden toegeschreven aan een relatief extensieve teeltmethode en hogere opbrengsten per hectare voor tweede generatie gewassen. Het grootste deel van de agrarische residuen kan beschikbaar komen tegen 1–4 € GJ^{-1}, voor bosbouwresiduen residuen ligt dit kostenniveau op 2–4 € GJ^{-1}.

De kansen voor energiegewasproductie over de tijd zijn ruimtelijk ongelijk verdeeld in Europa, waarbij de CEEC de meest interessante regio is met relatief hoge productiepotentiëlen tegen lage kosten. Delen van Polen, de Baltische staten, Roemenie, Bulgarije en Oekraïne zijn het meest veelbelovend. In West Europa zijn Frankrijk, Spanje en Italië redelijk interessant gemeten naar potentieel en kosten criteria. Hoewel het grote productiepotentieel over de tijd gehandhaafd zal blijven geldt dit niet per se voor de productiekosten wanneer economische groei zorgt voor een welvaartsniveau in de CEEC dat convergeert naar dat van de WEC.

De beschreven bevindingen zijn gebaseerd op de aanname dat de benodigde hoeveelheid landbouw- en grasland voor de Europese voedselproductie over de tijd zal afnemen wanneer de opbrengsten per hectare (voor voedselgewassen en dierlijke productie) geleidelijk toenemen, in lijn met historische ontwikkelingen. Landbouwgrond dat zodoende kan worden vrijgemaakt kan nog worden aangevuld met land dat (op dit moment al) braak ligt. Naast de veronderstelde opbrengststijgingen sturen twee andere factoren de mate waarin en snelheid waarmee Europese biomassapotentiëlen zich kunnen ontwikkelingen, zoals een verandering in de geaggregeerde voedselvraag onder invloed van populatie en gemiddelde dieetontwikkelingen, en de netto Europese handelsbalans voor voedsel en diervoeders. Van deze drie factoren is het verhogen van de opbrengstniveaus de meest belangrijke factor om het biomassapotentieel in Europa te ontwikkelen.

Om te evalueren hoe snel en in welke mate toekomstige opbrengstniveaus zich kunnen ontwikkelen – door economische, politieke en technologische factoren – is een analyse van historische opbrengstontwikkelingen gemaakt over de afgelopen vijf decennia in Europa. Twee aspecten vallen op: ten eerste zijn opbrengstniveaus significant gestegen in de laatste vijf decennia. De productie van voedselgewassen en die van dierlijke producten laten een gemiddeld jaarlijks groeitempo zien van 1.6%. In relatieve termen zijn ontwikkelingen trager in Nederland en Frankrijk met 1.0% y^{-1} dan in Polen en Oekraïne met 2.2% y^{-1}. In absolute getallen daarentegen is de toename in de WEC aanzienlijk geweest en bescheiden in de CEEC. Als gevolg hiervan hebben de WEC meer van hun agro-ecologische potentieel gerealiseerd vergeleken met de CEEC, wat betekent dat er nog een significant groeipotentieel ligt in de CEEC. Ten tweede is er een duidelijke relatie te zien tussen de gerealiseerde opbrengstenverbeteringen en de implementatie van landbouwbeleid gericht op het vergroten van de productie. Dit geldt zowel in tijden waarin opbrengsten zijn toegenomen als in perioden waarvoor een dalende trend is te zien. In periodes en in landen met stimulerend beleid (zoals interventieprijzen) gingen opbrengstniveaus omhoog; omgekeerd gingen deze niveaus zonder beleid of na afschaffing van beleid omlaag. Voorts laten trendontwikkelingen zien dat significante opbrengstverschuivingen kunnen worden gerealiseerd in een korte periode. Samenvattend kan worden gesteld dat de uitkomsten aangeven dat opbrengstniveaus actief kunnen worden gestuurd door politieke stimuleringsmaatregelen en economische ontwikkelingen in plaats van dat deze uitsluitend de uitkomst zijn van autonome ontwikkelingen zoals economische groei.

Onderzoeksvraag 2: In welke mate kunnen biomassapotentiëlen in Europa duurzaam worden gerealiseerd zonder het veroorzaken van negatieve effecten op het milieu of conflicten met voedselproductie?

Een belangrijke bevinding is dat het, binnen de Europese landbouw, mogelijk is om grootschalige biomassaproductie te combineren met voedselproductie op huidige niveaus, zonder directe of indirecte landgebruikveranderingen, terwijl er tegelijkertijd significante (netto) cumulatieve reducties van broeikasgasemissies kunnen worden gerealiseerd. Om de totale opbrengst van de Europese landbouw te verhogen zonder daarvoor extra land in cultuur te hoeven nemen zijn opbrengstverhogingen de geëigende weg. De hiervoor benodigde rationalisatie van de landbouw, met groeisnelheden in lijn met historische ontwikkelingen, binnen de agro-ecologische grenzen, kan geleidelijk de hoeveelheid landbouwgrond die nodig is voor de voedselproductie reduceren.

Ervaringen met intensivering in het verleden laten zien dat perioden met grote groei in opbrengstniveaus niet altijd samenvallen met perioden waarin grondstoffen doelmatig worden gebruikt. Een voorbeeld hiervan is het beleid van interventieprijzen. Dat zorgde weliswaar voor investeringen in een intensievere landbouw, met vooral meer kunstmestgebruik, leidend tot hogere opbrengstniveaus, maar tegelijkertijd tot meer inefficiënties bij gebrek aan een economische drijfveer om doelmatig met productiemiddelen om te gaan. Dit heeft onder andere geleid tot negatieve effecten op het milieu zoals verzuring en eutrofiëring. De introductie van gericht milieubeleid (als reactie hierop) laat echter zien dat dit beleid een stimulans kan zijn om efficiënter met beperkte grondstoffen om te gaan. Dit illustreert vooral het belang van het voeren van beleid dat gericht is op het stimuleren van opbrengsten en *input-output* efficiëntie, waardoor milieu-impacts geminimaliseerd worden en een duurzame productie gewaarborgd.

De netto broeikasgasbalans van de Europese landbouwgrond in de periode 2004-2030 is geëvalueerd voor diverse landgebruikvarianten, uitgesplitst naar emissies van stikstofoxiden (N_2O), de netto fluxen van bodem organische koolstof (Soil Organic Carbon, SOC) en de vermeden emissies door het vervangen van fossiele transportbrandstoffen door biobrandstoffen. Het handhaven van de huidige landbouw productie resulteert in 4.9 $GtCO_2$-eq. cumulatieve N_2O emissies tot 2030. Geïntensiveerde voedselproductie en productie van energiegewassen op vrijgekomen landbouwgrond in combinatie met het invoeren van mitigatiemaatregelen kan voor broeikasgasemissies de cumulatieve emissies van eenjarige gewassen significant reduceren. Wanneer olie, zetmeel en suikergewassen worden gebruikt als een energiegewas op deze vrijgekomen landbouwgrond dan worden cumulatieve emissies gereduceerd tot respectievelijk 1.9, 1.5 en 2.1 $GtCO_2$-eq. In het geval dat meerjarige gewassen worden geproduceerd kunnen de cumulatieve emissies zelfs omslaan in een cumulatieve mitigatie en wordt de landbouwgrond een netto vastlegger met gemitigeerde emissies van 3.3 en 4.5 $GtCO_2$-eq. respectievelijk voor grassen en bomen. Als gevolg van een hogere benodigde kunstmestgift voor meerjarige gewassen zullen de stikstofoxide emissies toenemen. De netto vastlegging is onder andere het gevolg van een tijdelijke toename in de vastlegging van SOC maar vooral door het vervangen van fossiele- door biobrandstoffen en de daarmee vermeden emissies.

Het werkelijke broeikasgas mitigatiepotentieel dat gerealiseerd kan worden in Europa hangt af van twee belangrijke voorwaarden: ten eerste, een geleidelijke intensivering van voedselproductie kan emissies in het landbouwsysteem als geheel verminderen. De toename van N_2O emissies als gevolg van een hogere (kunst)mestgift aan voedselgewassen kan (meer dan) worden gecompenseerd door vrijgekomen landbouwgrond een extensieve bestemming te geven. Het voldoen aan deze voorwaarde vermijd indirecte landgebruikveranderingen omdat een geleidelijk uitbreiding van het biomassa-productieareaal in balans is met verbeterd agrarisch management. Modelsimulaties bevestigen dat het mitigatiepotentieel van biomassaproductie op vrijgekomen landbouwgrond maximaal is wanneer meerjarige grassen en houtachtige gewassen worden geproduceerd in plaats van eenjarige gewassen. Dit kan worden verklaard door drie kenmerken van meerjarige gewassen; ze vereisen minder intensief management, ze hebben een hogere (kunst)mestefficiëntie en ze hebben over het algemeen een hogere opbrengst per hectare, zowel wat betreft de droge biomassa als in biobrandstof equivalent. Daarnaast zijn meerjarige gewassen geschikt om te worden geproduceerd op laagwaardiger gronden, wat resulteert in betere milieuprestaties (zoals een toegenomen bodem koolstofvoorraad en minder uitspoeling van nutriënten) vergeleken met de productie van eenjarige gewassen op dergelijke gronden. Ten tweede, de implementatie van structurele verbeteringen in het agrarische management zouden een integraal onderdeel moeten vormen van elke poging om landbouw te intensiveren en energiegewassen te produceren. De uitkomsten van de analyse laten drie maatregelen zien die direct kunnen worden geïmplementeerd: beperkte grondbewerking, bodemkoolstof verrijking en efficiëntere bemesting.

Onderzoeksvraag 3: Wat zijn mogelijke diffusiepaden van verschillende concurrerende biobrandstofroutes uitgesplitst naar ontwikkelingen in biomassa grondstofproductie en conversietechnologieën, gegeven hun huidige en toekomstige economische prestaties?

Het is de verwachting dat de bijdrage van energiegewasproductie aan het totale biomassa-aanbod toe zal nemen. Waar momenteel vaste biomassa vooral wordt gebruikt voor de productie van warmte en elektriciteit, zal deze toepassing op termijn meer concurrentie ondervinden van de productie van geavanceerde biobrandstoffen. Wat betreft de concurrentie tussen eerste en tweede (geavanceerde) biobrandstoffen spelen twee factoren een belangrijke rol: de opbouw van de kosten in de aanvoerketen (grondstof- en conversiekosten) en de economische vooruitzichten van deze kostenfactoren. Het gaat dan vooral om de mate waarin en snelheid waarmee deze kosten in de toekomst kunnen dalen als ze vaker worden ingezet. Eerste generatie biobrandstoffen hebben hogere grondstofkosten en lagere conversiekosten terwijl tweede generatie biobrandstoffen lagere grondstofkosten en hogere conversiekosten hebben. De consequentie hiervan is dat eerste generatie aanvoerketens vooral afhankelijk zijn van vooruitgang in de grondstofproductie terwijl tweede generatie aanvoerketens vooral afhankelijk zijn van kostendalingen in (kapitaal intensieve) conversietechnologieën.

Uitgaande van de huidige economische prestaties van grondstofproductie en conversietechnologieën en hun toekomstige vooruitzichten kan een modelsimulatie inzicht geven in hoe de verschillende aanvoerketens zich over de tijd in onderlinge concurrentie in de markt zullen ontwikkelen. Voorts is de invloed van exogene marktontwikkelingen (zoals hogere materiaalprijzen) en beleidskeuzen (zoals een gescheiden bio-diesel en bio-ethanol doelstelling) geëvalueerd. Enkele observaties worden hieronder besproken. Ten eerste, de finale kosten van tweede generatie biobrandstoffen worden verwacht ergens gedurende de komende twee decennia onder de kosten van eerste generatie biobrandstoffen uit te komen. Ambitieuze beleidsdoelstellingen kunnen de vraag naar grondstoffen opdrijven en zo de marktintroductie en diffusie van tweede generatie biobrandstoffen stimuleren. Als gevolg hiervan kunnen tweede generatietechnologieën worden opgeschaald, operationele ervaring opdoen en zodoende geleidelijk productiekosten reduceren. De beschreven dynamiek illustreert dat het marktvolume cruciaal is voor nieuwe productieketens om te leren en daarmee kosten te reduceren. Verschillende tweede generatie biobrandstofroutes concurreren met elkaar. Het moment van marktintroductie is cruciaal voor de toekomstige marktpenetratie. Verder redenerend in de trant van de leercurvebenadering: op het moment dat een technologie begint te produceren wordt operationele ervaring opgedaan waardoor de productiekosten van de betreffende technologie worden gereduceerd wat de technologie een relatief concurrentievoordeel geeft ten opzichte van een technologie die stagneert. Hieruit volgt dat bij twee concurrerende technologieën die op het punt staan de markt te betreden de commerciële vooruitzichten van de technologie die het laatste de markt betreedt afnemen. Dit pleit voor het streven naar een portfolioaanpak om *lock-in* effecten te voorkomen door de introductie van een (mogelijk suboptimale) technologie in de vroege fase van marktontwikkeling. Een specifieke beleidsmaatregel met betrekking tot biobrandstoffen die een portfolio aanpak kan aanmoedigen is het differentiëren van biobrandstof (bijmeng) doelstellingen in een doelstelling voor benzinevervangers en een voor dieselvervangers. Ten tweede, wanneer de kapitaalkosten voor conversietechnologieën proportioneel voor alle technologieën omhoog zouden gaan, bijvoorbeeld als gevolg van toegenomen materiaalprijzen, dan zou dit eerste generatie technologieën een relatief voordeel geven ten opzichte van tweede generatie conversietechnologieën. Dit zou de marktintroductie van tweede generatie technologieën kunnen vertragen waardoor deze laatste pas de markt zal betreden na een periode variërend van enkele jaren tot een decennium. Omgekeerd zouden lagere materiaalprijzen tweede generatie biobrandstoffen stimuleren.

Een voorwaarde voor het opschalen en ontwikkelen van een tweede generatie biobrandstofindustrie is de beschikbaarheid van een stabiel en voldoende groot aanbod van lignocellulose grondstoffen. Voor het bereiken van voldoende marktvolume kan de elektriciteit- en warmtesector een belangrijke rol spelen in de opbouw van voldoende capaciteit omdat productie van elektriciteit en warmte op basis van lignocellulose grondstoffen voor diverse productieroutes vandaag de dag al kosteneffectief is. Om het aanbod van lignocellulose grondstoffen verder uit te breiden naast residuen en afval, vormt de productie van SRC gewassen een belangrijke grondstofcategorie. SRC gewassen kunnen wereldwijd in verschillende contexten worden geproduceerd. In deze dissertatie zijn de economische en opbrengstvooruitzichten geanalyseerd voor de productie van populier in Italië, wilg in Zweden en eucalyptus in Brazilië. De gemiddelde huidige productiekosten voor SRC zijn het hoogst voor populier (5.5 € GJ^{-1}), gevolgd door wilg (4.4 € GJ^{-1}) en eucalyptus (2.8 € GJ^{-1}). Een *bottom-up* kostenanalyse uitgaande van het volledige verbeterpotentieel op productieve gronden laat een minimum kosten-niveau zien in de orde van 2 € GJ^{-1} voor alle drie gewassen. Kostenontwikkelingen uit het verleden laten kostenreducties zien van grofweg twee-derde in de afgelopen decennia voor populier in Italië en eucalyptus in Brazilië. In het geval van Zweden zijn geen kostendalingen te zien in de voorbije decennia, in verband met de beperkte productievolumes tot nu toe. Over het algemeen hebben opbrengststijgingen de grootste bijdrage geleverd aan het reduceren van productiekosten. Opbrengstniveaus zijn verhoogd door het toepassen van verbeterde rassen, toegenomen mestgift, bestrijdingsmiddelengebruik, voortdurende mechanisering in planten, grondbewerking en oogst en door efficiëntieverbeteringen in het (lokale) transport.

Gebaseerd op beperkte historische opbrengst en kostendata zijn *progress ratios* (PRs) bepaald voor populierproductie in Italië en eucalyptusproductie in Brazilië. Braziliaanse eucalyptusproductie laat een steilere curve zien (63–73%) dan populier productie in Italië (71–78%). De gevonden *progress ratios* vallen in de brede bandbreedte (55–80%) die in literatuur is gevonden voor eenjarige gewassen. Gemiddeld genomen vallen de PRs voor zowel eenjarige- als meerjarige gewassen laag uit, vergeleken met andere energie technologiesystemen die een gemiddelde PR van 84% laten zien. De gevonden PRs voor meerjarige gewassen zijn gecombineerd met Europese en wereldwijde projecties van de vraag naar (primaire) biomassa om te analyseren hoe snel het gevonden minimum-kostenniveau van 2 € GJ^{-1} gehaald kan worden. Uitkomsten laten zien dat wanneer Europese biomassa ambities in toenemende mate worden ingevuld met Europees geproduceerde SRC productie kostenreducties door leren redelijk snel kunnen worden gerealiseerd. De minimale kostenniveaus voor populier- en wilgproductie kunnen worden bereikt tussen 2022 en 2027. Voor eucalyptus, gelet op de aanzienlijke productie tot nu toe, zullen kostenreducties naar verwachting trager verlopen en kan een minimum-kostenniveau worden bereikt tussen 2021 en 2030.

Aanbevelingen voor beleid en verder onderzoek

Gebaseerd op de bevindingen zijn aanbevelingen voor beleid en verder onderzoek geïdentificeerd.

Beleidsaanbevelingen

- De Europese commissie zou een integrale visie moeten ontwikkelingen op de beleidsdomeinen landbouwontwikkeling en duurzame energie. Een (gedeeltelijke) afstemming tussen, of integratie van, het gemeenschappelijk landbouwbeleid en de *renewable energy directive* kan evidente voordelen opleveren. Investeringen in een verbeterd agrarisch management bijvoorbeeld, om te voldoen aan de *cross-*

compliance standaarden van het GLB, kunnen tegelijkertijd substantiële broeikasgasemissie reducties behalen. Verder kan een verbeterde agrarische efficiëntie landbouwgrond vrijspelen die gebruikt kan worden voor de productie van energiegewassen voor de productie van biobrandstoffen. Het vervangen van fossiele- door biobrandstoffen kan ook financiële voordelen opleveren, bijvoorbeeld wanneer de gerealiseerde emissiereducties onder het *emission trading scheme (ETS)* gebracht zouden worden.

- Duurzaamheidsrichtlijnen kunnen worden verbeterd op basis van inzichten uit dit proefschrift, bijvoorbeeld met betrekking tot het vergroten van biomassaproductie (in Europa) met duurzaam uitgevoerde intensivering en verbeteringen in de agrarische efficiëntie. Zo'n strategie kan indirecte landgebruikveranderingen helpen voorkomen terwijl energiegewasproductie wordt uitgebreid in evenwicht met verbeterd agrarisch management. Dit kan leiden tot verbeterde milieuprestaties van de landbouwsector en kan nieuwe economische kansen creëren. Met andere woorden, het kan leiden tot synergieën tussen bio-energie en landbouw in plaats van conflicten.
- Energie gewasproductie, met name die van meerjarige gewassen geproduceerd in korte gewasrotaties, zijn gebaat bij opschaling van het productievolume en het opdoen van ervaring in verschillende contexten. Hiervoor is stabiel en gecoördineerd beleid op EU-niveau nodig. De uitkomsten laten zien dat een dergelijke beleidscontext voor aaneengesloten perioden (van tenminste tien jaar) nodig zijn om een commercieel gezonde bedrijfstak op te bouwen.
- De productie van energiegewassen en (geavanceerde) biobrandstoffen kan snel kosteneffectief worden. Investeringssubsidies in geavanceerde biobrandstoftechnologieën faciliteren de marktintroductie en de diffusie van dergelijk technologieën. Tegelijkertijd kunnen investeringen in SRC productie een groter deel van de productie van deze gewassen in Europa concentreren, hetgeen mogelijk grote baten kan opleveren op de korte termijn. Hiervoor is een gerichte en geharmoniseerde EU-brede beleidsaanpak nodig, om zowel de benodigde capaciteit voor lignocellulose grondstofproductie te realiseren als de commercialisatie van geavanceerde biobrandstoftechnologieën. Beide ontwikkelingen zijn nog niet voorzien in (veel van) de nationale duurzame actieplannen (*national renewable action plans*, NREAPs). In een dergelijk scenario zou de productie van lignocellulose gewassen, met hogere opbrengstniveaus, worden gestimuleerd die tegelijkertijd het vermogen hebben om meer broeikasgasemissies te vermijden dan wanneer fossiele transportbrandstoffen zouden worden vervangen door eerste generatie biobrandstoffen.

<u>Aanbevelingen voor verder onderzoek</u>

- Om de beleidsstrategieën zoals hierboven beschreven verder te bekrachtigen zou een nauwgezette kwantificering van investeringen in leren, en kosten en baten voor milieu, samenleving en macro-economie gewenst zijn. Dit zou kunnen worden vergeleken met een alternatief scenario waarin Europa in toenemende mate afhankelijk wordt van energie en biomassa importen van buiten de EU.
- Hoewel bio-energie productie milieuvoordelen kan opleveren zijn de effecten op de (agro-)biodiversiteit en waterschaarste nog matig begrepen; deze verdienen daarom aanvullend onderzoek.

- Verder onderzoek is nodig met betrekking tot ontwikkelingen in gewascultivering, zowel gericht op eenjarige als meerjarige gewassen, met een accent op de mogelijkheden om productiesystemen te laten leren en productiekosten te reduceren.
- In toekomstig onderzoek kan het toepassen van een multi-factor productiviteit (MFP) analyse worden overwogen met betrekking tot gedeelten van het agrarisch productiesysteem (zoals sub-sectoren binnen een land) om zo een kwantitatieve uitsplitsing te verkrijgen van welke productiefactoren in welke mate hebben bijgedragen aan historische opbrengstontwikkelingen in de landbouw.
- Verdere verfijning is mogelijk in het modeleren en het begrijpen van de ruimtelijke dynamiek van landgebruikverandering in relatie tot grootschalig biomassagebruik in verschillende sectoren. Ruimtelijk expliciete (GIS-gebaseerde) en multi-sectorale modelbenaderingen kunnen nieuw licht werpen op deze onderwerpen.
- De dynamiek in ontwikkelingen in de Europese zelfvoorzieningszekerheid voor voedsel en diervoeder (bijvoorbeeld in relatie to wereldwijde grondstofmarkten) kan worden verkend, bijvoorbeeld gebruik makend van algemene evenwichtsmodellen van het wereldwijde voedselsysteem.

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Marc

Curriculum Vitae

Marc de Wit *(1980)* studied Natural Sciences & Innovation Studies at Utrecht University. Specialising in Energy & Resources, he graduated (2006) on an assessment of the performance of onboard storage technologies in hydrogen fuelled vehicles. Prior to his master studies he completed (1999) the first year of the BSc program Applied Physics from the TH Rijswijk. After his MSc graduation Marc continued at Utrecht University in the Science, Technology and Society group as a bio-energy researcher and PhD fellow. Starting on the European Commission funded REFUEL project, he contributed to a road map for European biofuels; assessing biomass production potentials and costs, and modelling the competition dynamics between different biofuel routes. From 2008 onwards, he performed an analysis of developments in Europe's agricultural productiviy and an assessment of the environmental impacts associated with integrating large-scale biomass production into European agriculture. The latter assessments he conducted in collaboration with Wageningen University and the Energy research Centre of the Netherlands (ECN). During the last three years of his research Marc worked half-time at the Policy Studies Unit of ECN in Amsterdam.

Publications

Below a list of journal articles by the author. Chapter 4 and 5 of this dissertation are forthcoming.

1. **De Wit MP**, Londo HM, Faaij APC. *Development in European agriculture: Relations to and Opportunities for Bioenergy Production*, Renewable and Sustainable Energy Reviews 15 (2011) 2397-2412 >>
2. **De Wit MP**, Faaij APC. *European Biomass Resource Potential and Costs*, Biomass and Bioenergy 34 (2010) 188 – 202 >>
3. **De Wit MP**, Junginger M, Lensink S, Londo M and Faaij APC, *Competition Between Biofuels: Modelling Technological Learning and Cost Reductions over Time*, Biomass and Bioenergy 34 (2010) 203 – 217 >>
4. **De Wit MP**, Faaij APC. *Impact of Hydrogen Onboard Storage Technologies on the Performance of Hydrogen Fuelled Vehicles: A Techno-economic Well-to-wheel Assessment*, International Journal of Hydrogen Energy 32 (2007) 4859 – 4870 >>
5. Londo M, Lensink S, Wakker A, Fischer G, Prieler S, van Velthuizen H, **De Wit MP**, Faaij A, Junginger M, Berndes G, Hansson J, Egeskog A, Duer H, Lundbaek J, Wisniewski G, Kupczyk A, Könighofer K, *The REFUEL EU road map for biofuels: application of the project's tools to some short-term policy issues*, Biomass and Bioenergy 34 (2010) 244 – 250 >>
6. Fischer G, Prieler S, Velthuizen H van and Lensink SM, Londo M, **De Wit M**. Biofuel production potentials in Europe; Sustainable use of cultivated land and pastures. Part I: land productivity potentials, Biomass and Bioenergy 34 (2010) 159 – 172 >>
7. Fischer G, Prieler S, Velthuizen H van and Göran B, Faaij A, Londo M, **De Wit MP**. Biofuel production potentials in Europe; Sustainable use of cultivated land and pastures. Part II: Land use scenarios, Biomass and Bioenergy 34 (2010) 173 – 187 >>
8. Junginger M, **De Wit MP**, Sikkema R, Faaij APC. *International Bioenergy Trade in the Netherlands*, Biomass and Bioenergy 32 (2008) 672 - 687 >>
9. Junginger M, Bolkesjø T, Bradley D, Dolzan P, Faaij A, Heinimo J, Hektor B, Leistad Ø, Ling E, Perry M, Piacente E, Rosillo-Calle F, Ryckmans Y, Schouwenberg P, Solberg B, Trømborg E, da Silva Walter A, **De Wit MP**. *Developments in International Bioenergy Trade*, Biomass and Bioenergy 32 (2008) 717 – 729 >>

“Denkend aan Holland

Zie ik breede rivieren traag door oneindig laagland gaan,

rijen ondenkbaar ijle populieren als hooge pluimen aan den einder staan… “

MARSMAN (1936)