Quantification and comparison of the economic and GHG performance of biomass supply chains

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(met een samenvatting in het Nederlands)

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Chapter 1

Introduction

1.1 GHG emission reduction by biomass use

One of the sustainable development goals of the United Nations, also closely linked to the Paris Agreement at the COP21 in Paris in December 2015, is to *take urgent action to combat climate change and its impacts* (UN, 2017; UNFCC, 2017). There is a widespread scientific consensus that global climate change is *most likely* caused by the increased levels of anthropogenic greenhouse gasses (GHG) in the atmosphere (IPCC, 2014b). Continued emission of GHGs eventually lead to irreversible and severe impact on people and ecosystems. Therefore, *substantial and* sustained anthropogenic GHG emission reductions are necessary to limit the impact of climate change (IPCC, 2014b). GHG emissions predominantly originate from the extraction and use of fossil resources, and from land conversion and land management practices (IPCC, 2014b).

The use of biomass for the production of heat, electricity, biofuels and chemicals is seen as an important GHG mitigation option (H. Chum et al., 2011; IPCC, 2014b). Biomass employment combined with Carbon Capture and Storage (BECCS) is a crucial component in many scenario studies to meet GHG emission targets for limiting global warming to 2°C. In 2014, bioenergy provided 10% (43 EJ_{PRIM}) of the world primary energy demand, of which 4.71% (27 EJ_{PRIM}) is qualified as modern biomass use (IEA, 2016; Kristin Seyboth et al., 2016). In 2015, dominant bioenergy commodities were the use of biomass for heat (14 EJ), liquid biofuels (133 billion litres), and the production of electricity (464 TWh) (Kristin Seyboth et al., 2016). The estimated global production capacity of biobased building blocks was estimated around 2.64 million tonnes in 2013 (Dammer, Carus, Raschka, & Scholz, 2013).

The biomass utilization for bioenergy and biobased chemicals is expected to increase in the coming decades due to, among others, support for GHG mitigation options, security of supply, and demand for more environmental friendly products (Jong, Higson, Walsh, & Wellisch, 2011; Lamers, Hamelinck, Junginger, & Faaij, 2011; Lamers, Junginger, Hamelinck, & Faaij, 2012a). The projected demand for bioenergy and biobased chemicals in climate change mitigation scenarios is in the range of 10 – 245 EJ_{PRIM}/year in 2050 (Creutzig et al., 2015; Daioglou, 2016; Ioannis Tsiropoulos, 2016). An increasing demand for biomass would inherently require an increase in supply. However, there is uncertainty regarding the biomass supply potential in the future. The estimated biomass supply potential for 2050 differs by up to three orders of magnitude in size (IPCC, 2014a). The review of Creutzig et al., (2015) qualified the sustainable biomass supply ranges according to their agreement among scientists; up to 100 EJ_{PRIM}/year in 2050 reached high agreement, while the range of 100-300 EJ_{PRIM}/year is qualified as medium agreement (Creutzig et al., 2015). Those levels of biomass supply include different categories of biomass resources: organic waste, forest and agricultural residues, additional wood extraction from forest and dedicated biomass plantations (Creutzig et al., 2015; IPCC, 2014a). Given that the biomass supply is limited, it is important to exploit its potential as GHG mitigation option effectively.

1.2 Challenge to large-scale biomass employment

Large-scale biomass supply and utilization raised concerns about the overall sustainability. These include e.g. the risk of low GHG benefits, impacts on water, soil and biodiversity, effects on food security and low economic viability (IPCC, 2014a). Two of these major concerns are addressed here; the net GHG emission reduction of biomass use and the economic performance of biobased supply chains.

Biomass utilization will not by default generate a GHG emission reduction compared to the fossil reference. The CO_2 emissions from biomass combustion are, or have been sequestrated during biomass growth (Göran Berndes et al., 2016). However, GHGs are emitted during the life cycle (related to the cultivation, transport, processing, use and combustion of biobased fuels and chemicals) and due to land use changes (LUC) resulting from biomass production. The lifecycle and LUC related GHG emissions of biomass supply chains vary widely between biomass supply chains and between geographical regions. Therefore region- and supply chain specific GHG performance assessment is required to identify promising routes for GHG emission reduction.

The economic viability of biomass use is an important driver for large-scale utilization. The production of biobased electricity, fuels and chemicals should be able to compete economically with fossil equivalents. Several biomass supply chains are economically competitive today, others require significant cost reduction to become economically attractive (H. Chum et al., 2011). Different biomass supply chains have improved their economic performance (IPCC, 2014a). In the coming decades, the economic performance of existing biomass supply chains can be improved, while the use of novel combinations of biomass feedstock and industrial processing options may provide additional biomass use options. The economic performance of biomass supply chains vary widely across geographical regions and biomass resource types (H. Chum et al., 2011) Therefore, a detailed region specific quantification of the current and future economic performance is crucial to identify potentially viable biomass supply chains.

A region specific assessment of the GHG and economic performance of current and future biomass supply chains could contribute to the efficient and effective use of biomass for GHG emission reduction.

1.3 Knowledge gaps

1.3.1 GHG balance of biomass supply chains

GHG emissions occur throughout the life-cycle of biomass use for heat, electricity, fuels and chemicals related to biomass cultivation, mobilization, industrial processing, use, and end-of-life phases. In addition, GHGs are emitted due to land use change resulting from biomass production. For this dissertation the main focus is on GHG emission associated with biomass supply, including direct carbon stock change, logistics and conversion to biofuels and biobased chemicals. The *GHG emissions in the supply chain* of biobased electricity, fuels and chemicals consider the GHG's of all stages in the cultivation, mobilisation, harvest, transport and processing of biomass. Earlier studies assessed the GHG emissions of biomass cultivation, transport and processing, e.g. (de Souza Dias et al., 2015; Hoefnagels, Searcy, et al., 2014; Hoefnagels, Smeets, & Faaij, 2010; Wang, Han, Dunn, Cai, & Elgowainy, 2012) (Cok, Tsiropoulos, Roes, & Patel, 2013; de Souza Dias et al., 2015; Gerbrandt et al., 2016; Hill, Nelson, Tilman, Polasky, & Tiffany, 2006; Renouf, Wegener, & Nielsen, 2008). Important elements contributing to GHG emissions of biomass supply chains are the use of fertilizers, diesel consumption of machinery and the consumption of heat and electricity in industrial processing (Kendall & Chang, 2009; Macedo, Seabra, & Silva, 2008; Ioannis Tsiropoulos et al., 2014). The application rate of fertilizers and diesel consumption vary significantly per biomass type, soil conditions, and potential biomass yield (Hoefnagels et al., 2010). These studies have generated vital insights, for example regarding the contribution of the different stages, potential improvement options or ranking of different biomass supply chains. However, these LCA-type studies often neglect the GHG emissions related to the expansion of biomass supply. Expansion of biomass supply may occur via the expansion of land area, or adaptations to land management strategies which are both associated with carbon stock changes.

The cultivation of *dedicated crops* for bioenergy and materials results in LUC: land use is changed from a previous use to the cultivation of biomass feedstock. The conversion of land from its original use to the cultivation of biomass for energy and materials could result in carbon sequestration (removing CO_2 from the atmosphere) or in carbon emissions, due a change in carbon pools (above- and below-ground biomass, soil organic carbon, dead organic matter (IPCC, 2006). The potential impact of LUC emissions on the GHG mitigation of biomass supply chains is highlighted in several studies (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Melillo et al., 2009; Timothy Searchinger et al., 2008). The amount of land-use change resulting from a given amount of biobased product is affected by the biomass yield and biomass conversion efficiency. While there is a considerable potential for improvements (Plevin, Beckman, Golub, Witcover, & O'Hare, 2015), many studies neglect potential developments in yield and efficiency. The GHG emissions related to LUC depend on the land use that is replaced, the type of biomass cultivated after conversion, the management of land before and after conversion, and the local biophysical characteristics such as soil and climate conditions (Gibbs et al., 2008; Floor Van Der Hilst & Faaij, 2012), which are in many cases spatially highly heterogeneous. Only few studies (e.g. (Almeida et al., 2016; Floor Van Der Hilst & Faaij, 2012; Floor van der Hilst, Verstegen, Zheliezna, Dorzdova, & Faaij, 2014; Pogson et al., 2016)) takes this spatial variability into account.

For *forest biomass* the carbon stock change due to the initial harvest for biomass supply is called the carbon debt of woody biomass production. The time to offset the carbon stock change is expressed as the carbon payback period[1] or carbon offset parity period[2]. These

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[1] According to (Mitchell et al., 2012) the losses in carbon storage associated with biomass harvest may require several years to recuperate. The period to recuperate through biomass re-growth and fossil fuel substitution is called carbon debt payback period.

[2] The carbon offset parity period is similar to the carbon debt payback period, only the recuperation is not compared to the initial carbon stock change but to the carbon stock of the counterfactual scenario of the same forest plot.

periods describe the time required for the biomass supply chain to provide a net GHG emission benefit compared to a static or dynamic baseline (Bentsen, 2017; Mitchell, Harmon, & O'Connell, 2012). Previous work have quantified the carbon payback periods and carbon offset parity periods for a wide range of biomass supply chains within different world regions (Colnes et al., 2012; Schlamadinger & Marland, 1996; Walker, et al., 2010; Zanchi, Pena, & Bird, 2010). These estimated carbon payback or offset parity periods are influenced by the applied methodological perspective for carbon accounting (Creutzig et al., 2015) and the case-study specific characteristics such as the initial carbon stock change, forest growth rates, GHG emission avoidance, and the counterfactual scenario (Lamers & Junginger, 2013). Earlier studies found long carbon payback periods considering the conversion of high carbon stock land to a biomass system with low GHG avoidance per hectare (John McKechnie, Colombo, Chen, Mabee, & Machlean, 2011; Mitchell et al., 2012). Shorter carbon payback periods were found when converting low carbon stock land with an efficient biomass supply system with high GHG emission avoidance (Mitchell et al., 2012; Zanchi et al., 2010). While additional removals from forests and dedicated plantations are expected to provide a large contribution to future biomass supply (IPCC, 2014a; Turhollow et al., 2014), only few studies quantified the carbon payback period and carbon offset parity periods for fast growing forest plantations (Colnes et al., 2012; McKechnie et al., 2011; Walker, et al., 2010). In forest plantations, the plantation management strategy can be altered to maximise the production of bioenergy feedstock. This may include increased planting density, additional thinning and/or shortening the rotation period to increase annualised wood production per hectare (Perlack & Stokes, 2011; Scott & Tiarks, 2008). Although the impact of forest plantation management on the economic performance has been quantified often e.g. (Dickens & Will, 2004; Straka, 2014; Susaeta, Lal, Alavalapati, Mercer, & Carter, 2012a), the impact on GHG balances is quantified in only few studies; e.g.: (Bentsen, 2017; Cintas et al., 2017; Dwivedi, et al., 2012; Dwivedi & Khanna, 2015).

To quantify and compare the GHG performance of biomass supply chains the GHG balance should include both supply chain and LUC related GHG emissions. The GHG balance is influenced by the GHG accounting method, as well as by e.g. the biomass feedstock selection, plantation management, biomass yield and selection of conversion technology. These characteristics are site and case study specific, and change over time. Therefore, the GHG balance of current and future biomass supply chains should be quantified with a uniform approach while taking into account case-specific parameters.

1.3.2 Economic performance of biomass supply chains

The economic performance of biomass supply chains is often seen as potential barrier for large-scale employment (De Meyer, Cattrysse, Rasinmäki, & Van Orshoven, 2014; IPCC, 2014a). Although several existing biomass supply chains are in an economically competitive range with fossil equivalent products, many others require costs reductions, either by improvement of current supply chains or the development of novel concepts (H. Chum et al., 2011). To quantify the economic performance of biomass supply chains two main approach can be distinguished; 1) top down analysis (Daioglou, Wicke, Faaij, & van Vuuren, 2015) (Fujimori, Masui, & Matsuoka, 2014; Suttles, Tyner, Shively, Sands, &

Sohngen, 2014) and 2) bottom-up approaches (J. G G Jonker & Faaij, 2013). Furthermore, studies can be categorized according to their regional scope; ranging from a global coverage to a region specific supply chain. Bottom-up assessments are studies assessing a location specific and product specific supply chain with high level of precision and low level of data aggregation (Ioannis Tsiropoulos, 2016). Such studies are usually focussed on one specific biomass system and so, are able to gain a detailed quantification of its performance, and potentially its improvement options. Bottom-up studies highlighting the economic performance of biomass crop production, biomass transport options, secondary bioenergy carriers or biobased chemicals are plentiful, e.g. (de Souza Dias et al., 2015; Hill et al., 2006; Macrelli, Mogensen, & Zacchi, 2012; Olofsson, Barta, Börjesson, & Wallberg, 2017). These studies show the important interplay between the different elements of the biomass supply chain: biomass feedstock production, harvest, transport and industrial processing. Top-down approaches are a more aggregated representation of the supply chains involved, which allows for a sectoral or economy-wide perspective and the potential interaction or integration with other relevant systems (Wicke et al., 2015). To quantify the economic performance of specific biomass feedstock, industrial processing options or biomass supply chains with low level of data aggregation, the use of bottom-up assessments is preferred. This low level of data aggregation provides detailed insights in the performance of the supply chain under study. However, despite the large amount of bottom-up assessments of individual biomass supply chains, among others (Batidzirai, Hilst, Meerman, Junginger, & Faaij, 2013; Chovau, Degrauwe, & Van der Bruggen, 2013; Daystar, Reeb, Gonzalez, Venditti, & Kelley, 2015; Dias, Cunha, et al., 2011), a uniform comparison is difficult due to differences in e.g. geographical scope, system boundaries, economic approach, or selection of biomass crop and conversion technology. To enable a comparison between the economic performance of different biomass supply chains the use of a uniform approach, with similar economic assumptions, scale, etc., is required. To determine the costs for biomass employment compared to a fossil reference, a comparable unit of analysis should be chosen. Uniform, harmonized economic assessments to quantify and compare the economic performance of different biomass supply chains are largely lacking.

Considering the knowledge gaps in sections 1.3.1 and 1.3.2, important topics for research are: 1) the methods used for the quantification of the economic performance and GHG emission reduction potential of biomass use, 2) regional specific case studies for the economic performance and GHG emissions of large-scale production of electricity, fuels and chemicals. Furthermore, a detailed quantification of the economic performance and GHG balance also shows the trade-off between these key indicators.

1.4 Geographical scope of the dissertation

The GHG balance and economic performance of biomass production and use are biomass supply chain and site-specific. Different biomass types are produced around the globe to produce a variety of biobased fuels, electricity and chemicals. Two important biomass production chains are the wood pellet production in the Southeastern USA, mainly for overseas electricity production and the sugarcane - ethanol production in Brazil. These regions are key biomass producers and make an important contribution to the global bioenergy supply. Both production regions have the potential to significantly expand their production in the coming decades, by the expansion of the cultivation area, improvements in agricultural or industrial yield and the introduction of new industrial processing pathways.

In 2015, the wood pellet export of the United States was approximately 4.5 Mtonne, mainly for power generation in the United Kingdom and Benelux (Kristin Seyboth et al., 2016). In recent years the export of wood pellets from the United States has increased rapidly, mainly due to the large increase in production capacity in the Southeastern United States (Lamers, Junginger, Hamelinck, & Faaij, 2012b). Softwood plantations in the Southeastern United States are recognized as potential biomass feedstock to meet the domestic as well as transatlantic demand for bioenergy (Dwivedi, Johnson, Greene, & Baker, 2016; Goh et al., 2013; Perlack & Stokes, 2011).. Currently, harvested softwood is used to produce a variety of timber products , including sawtimber, pulpwood, veneer logs, plywood, industrial fuel, and other wood products (Oswalt, Smith, Miles, & Pugh, 2014). The demand for wood pellets is expected to increase considerably in the coming decades, while the demand for other wood products is also expected to increase (Oswalt et al., 2014). Plantation management strategies can be adapted to meet the demand for bioenergy and wood products (Perlack & Stokes, 2011). The expected increase in wood pellet production in the southeast of the US and the potential adaptation in management and yield of softwood plantations, biomass yield development in recent decades and the potential adaptations of forest plantation management strategies to increasing demand for low-costs biomass feedstock, the Southeastern USA are an interesting region for research.

Brazil has long standing history in the production of first generation ethanol production from sugar cane and is a key ethanol production region (Kristin Seyboth et al., 2016; van den Wall Bake, Junginger, Faaij, Poot, & Walter, 2009). Sugarcane harvest season 2015/2016 yielded a total of 605 Mtonne for the production of 34 million tonnes sugar and 30 billion litres ethanol (UNICA, 2017). The total cultivation area was approximately 9 Mha (CONAB, 2015). Brazilian first generation ethanol substituting gasoline results in high GHG emission reduction (excl. land-use change GHG emissions) due to the high sugarcane yield, the high industrial conversion efficiencies and the co-production of electricity (J. Seabra, Macedo, Chum, Faroni, & Sarto, 2011; Ioannis Tsiropoulos et al., 2014). Brazil has the potential to expand the ethanol production to meet the increasing domestic demand and to contribute to achieving global biofuel mandates (Walter, Rosillo-Calle, Dolzan, Piacente, & Borges da Cunha, 2008). The sugar cane area is expected to increase with 6.4 Mha by 2021 (Goldemberg, Mello, Cerri, Davies, & Cerri, 2014). In 2015 in Brazil, two industrial ethanol processing plants started operation using sugarcane bagasse and straw (Kristin Seyboth et al., 2016). The development of second generation industrial processing also enables the use of other ligno-cellulosic biomass feedstocks for the production of ethanol and other biobased chemicals. Given the combination of an existing ethanol industry, potential expansion of ethanol production, and the different potential ethanol and advanced biobased production pathways, Brazil is an interesting region to study the economic performance and GHG balance of biomass supply chains.

1.5 Research questions and outline of the dissertation

The aim of this thesis is to assess, combine, and harmonize different methods to uniformly quantify and compare the GHG emissions and economic performance of regional specific biomass supply chains. In this dissertation biomass supply chains include the cultivation, transport and processing stage. To this end, the following research questions are addressed:

1. How to uniformly quantify the total GHG balance of biobased supply chains for the production of electricity, fuels and chemicals, and what are the GHG emission balances for specific regional case studies?
2. How to uniformly quantify the economic performance of biobased supply chains for the production of electricity, fuels and chemicals, and what is the economic performances of specific regional case studies?
3. What are the trade-offs between the GHG balance and economic performance of different biobased supply chains for different regions?

These research questions are addressed in chapters 2-6. Chapter 2 and 3 focus on the GHG balance and economic performance of wood pellet production in the southeast of the US. Chapter 4-6 focus on ethanol and advanced biomass supply chains in Brazil. See Table 1-1 for an overview of the different chapters, and the addressed research questions.

Table 1-1 Overview of the research questions addressed in each chapter

Chapters		Research question		
		1	2	3
2	Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States	x		
3	Carbon balances and economic performance of pine plantations for bioenergy production in the Southeastern United States	x	x	x
4	Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies		x	
5	Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil	x	x	x
6	Economic performance and GHG emission intensity of sugarcane and eucalyptus derived biofuels and biobased chemicals in Brazil.	x	x	x

Aim and focus of different chapters

Chapter 2 examines the effect of methodological perspectives on the estimated carbon payback time and offset parity point for wood pellet production from softwood plantations in the Southeastern United States. The chapter explains the concepts of carbon payback time and carbon offset parity periods and the different methodological perspectives that can be applied. A carbon accounting model is used to model the carbon balance of a low-, medium- and high-yield softwood plantation for a single stand level, an increasing stand and a landscape level. The GHG balances include forest carbon pools, GHG emissions of silvicultural practices, and emission related to transportation and pelletizing. Also the avoided GHG emissions due to fossil fuel substitution are taking into account.

Chapter 3 quantifies the impact of plantation management choices on the GHG balance and economic performance of bioenergy production using loblolly pine in the Southeastern USA. The plantation management strategies assessed in this study (conventional, additional thinning and short rotation), are characterised by planting density, thinning age, and rotation period. The plantation management strategies affect both the overall yield of the loblolly pine plantation as well as the composition of the yield in terms of different wood classes (sawtimber, chip-n-saw and pulpwood and slash). Each strategy is considered with and without the collection and utilization of slash residues for bioenergy. A spreadsheet model is constructed to calculate the total carbon balance and economic performance of the different loblolly pine plantation management strategies. The total carbon balance is the sum of the in-situ (carbon in live trees, decaying carbon in dead trees and harvest residues) and ex-situ (embedded biogenic carbon in harvested wood products and displaced fossil carbon due to product displacement) carbon pools.

Chapter 4 presents an economic outlook of the ethanol industry in Brazil considering different biomass feedstocks and different industrial processing options. With the ongoing research and development in biomass cultivation of different ethanol feedstock and industrial processing pathways the ethanol production costs are likely to change in the future. This study focusses on the current and future ethanol production costs in Brazil, considering the utilization of different production configurations. A spreadsheet model was designed to account for different feedstocks and industrial processes, and expected trends in biomass yield, sugar- and fibre content, industrial scale and efficiency. The model is used to calculate the development in bottom-up cost structures of feedstock cultivation, transport and industrial processing between 2010-2030.

Chapter 5 uses the key findings from chapter 4 and uses it in a optimization model to determine the optimal location and scale of the expansion of biomass production in the state of Goiás between 2012 and 2030. This expansion not only includes the expansion of cultivation area in great detail, but also the increase of biomass yield and improved conversion efficiency to ethanol up to 2030. A linear optimization model is utilized to determine the economically optimal location and scale of industrial processing plants given the projected spatial distribution of the expansion of sugarcane and eucalyptus production in the state of Goiás between 2012 and 2030. Three expansion approaches evaluated the impact on ethanol production costs of expanding an existing industry in one time step (one-step), or multiple time steps (multi-step), or constructing a newly emerging ethanol industry in Goiás (greenfield). In addition, the GHG emission intensity of the optimized ethanol supply chains are calculated, taking into account both land-use change emissions as well as supply chain GHG emissions.

Chapter 6 aims to uniformly quantify the factory gate production costs and GHG emission intensity of biobased ethanol, ethylene, 1,3 propanediol and succinic acid, and compares these to their respective fossil references. A uniform framework is applied to determine the production costs and GHG emission intensity, including feedstock supply, biobased product yield, capital investment, energy, labour, maintenance and processing inputs. To quantify the potential range of final results due to these ranges, both a sensitivity analysis and an uncertainty analysis are performed. The results of these analysis quantify the potential range of production costs and GHG emissions of the biobased products given the uncertainty in the key parameters. The different ranges are compared to the range in factory gate production costs and GHG emission intensity of the fossil equivalent products.

Lastly, **chapter 7** summarizes the research context, objectives, research questions and key findings of this dissertation. This chapters answers the research questions by highlighting the overarching themes and specific characteristics of the different regional biobased supply chains. Furthermore, recommendations are made for industry stakeholders and policymakers as well as directions for further research.

Chapter 2

Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States

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Abstract

This study examines the effect of methodological choices to determine the carbon payback time and the offset parity point for wood pellet production from softwood plantations in the South-eastern United States. Using the carbon accounting model GORCAM we model low-, medium- and high-intensity plantation management scenarios for a single stand level, an increasing stand level and a landscape level. Other variables are the fossil-fuel reference system and the electrical conversion efficiency. Due to the large amount of possible methodological choices and reference systems, there is a wide range of payback times (<1 year at landscape to 27 years at stand level) and offset parity points (2–106 years). Important aspects impacting on the carbon balances are yield, carbon replacement factor, system boundaries and the choice of reference scenario used to determine the parity point. We consider the landscape-level carbon debt approach more appropriate for the situation in the Southeastern United States, where softwood plantation is already in existence, and under this precondition, we conclude that the issue of carbon payback is basically nonexistent. If comparison against a protection scenario is deemed realistic and policy relevant, and assuming that wood pellets directly replace coal in an average coal power plant, the carbon offset parity point is in the range 12–46 years; i.e. one or two rotations. Switching to intensively managed plantations yields most drastic reduction in the time to parity points (<17 years in 9 of 12 cases).

2.1 Introduction

The use of biomass for energy and materials is considered an essential alternative to fossil fuel consumption, thereby reducing GHG emissions (H. Chum et al., 2011). To stimulate bioenergy consumption, different policies have been implemented around the world. Wood pellet consumption in Europe, for example, is mainly for residential heating, district heating and large-scale power production. The international trade of wood pellets is triggered by demand-side policies. Extra-EU trade of wood pellets is mainly with Canada, the United States of America (USA) and Russia. In recent years the export of wood pellets from the United States have increased rapidly, mainly due to the large production capacity increase in the South-eastern United States, to meet the demands of the European market (Lamers et al., 2012b). Our analysis focuses on the use of forestry biomass for wood pellet production. Forests are essential for both the large storage of carbon and the exchange (flux) of carbon with the atmosphere (Ingerson, 2007).

The conversion of biomass into energy will not by default generate sustainable bioenergy. According to Cherubini et al., (2009), the greenhouse gas balance of bioenergy systems is subject to differences in feedstock, conversion technology, end-use technology, system boundaries (fossil-fuel) reference system and regional differences. Sustainably produced bioenergy can reduce or avoid the GHG emissions from fossil fuels (H. Chum et al., 2011). Next to the overall greenhouse gas balance, carbon stock change induced by the use of biomass for energy have increasingly become part of public debate (including the time required before organic carbon released by combustion is recaptured through the uptake by plants). The carbon payback time of forestry biomass was already treated by Schlamadinger & Marland, (1996) in a study that compared different bioenergy crops, including the conversion of mature forest and agricultural land into bioenergy plantations. More recent publication include, among others, Colnes et al., (2012), Walker, et al., (2010), Zanchi et al., (2010), McKechnie et al., (2011), Mitchell et al., (2012) and Holtsmark, (2011).

The study by Zanchi et al., (2010) provides insights into the carbon neutrality of different bioenergy production systems. The carbon neutrality is based on the difference between the carbon emissions (or avoided emissions) of a bioenergy system compared with a fossil fuel system. Zanchi et al., (2010) reports results showing that the carbon payback period of short rotation forestry that has displaced high carbon stock mature forests can be as long as 150 years. Mitchell et al., (2012) provides a conceptual explanation on the difference between carbon payback and carbon parity point, see Figure 2-1 for a visual representation. The carbon payback period is the period between initial harvest and the point in time were the overall carbon balance equals the carbon storage before initial harvest, taken into account carbon debt and avoided fossil fuels. The carbon parity point is the time between initial harvest and the point in time when the utilization of forestry biomass is favourable over the reference scenario, again considering the carbon debt and (avoided) fossil fuel emissions (Mitchell et al., 2012). Walker, et al., (2010) found that the carbon payback period is 21 years when forestry biomass–based electricity is compared with electricity produced from coal, and more than 90 years for electricity produced from natural gas for a case study in Massachusetts. The carbon payback period was defined as the time period before the cumulative carbon flux of a bioenergy system equals a fossil-fuel reference system, taking into account a carbon debt for the bioenergy system. Essential variables are the (re) growth of biomass and fossil fuel emissions. The assessment of McKechnie et al., (2011) found similar results; after 17– 38 years wood pellet electricity production is beneficial over coal fired power from a greenhouse gas viewpoint. McKenzie plots the (decrease in) forest carbon stock while substituting fossil fuels at the same time. Mitchell et al., (2012) provides insights into the carbon payback period and the carbon offset parity point of forest bioenergy. Mitchell et al., (2012) concluded that the initial landscape conditions and land-use history were of major importance to the carbon payback period. The results range from a carbon payback period of 1 year for 'Post-agricultural landscapes' to 19–1000 years for 'Old-growth landscapes', the latter one due to the high carbon stocks before the initial harvest. Low carbon payback periods and low carbon offset parity points are reached with high yields and low initial carbon stock (before first harvest; Zanchi et al., (2010); Mitchell et al., (2012).

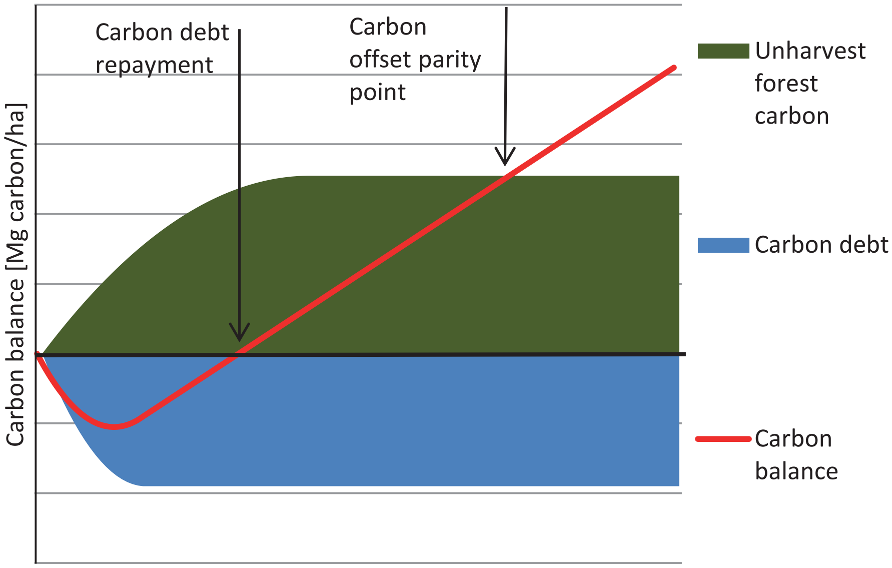

Figure 2.1 Visual representation of the carbon payback period and the carbon offset parity point on a stand level, taken from Mitchell et al., (2012).

In the study of Holtsmark, (2011), the typical life cycle of a spruce tree (growth phase, 100 years; mature stable phase, 100 years; standing dead tree, 30 years; decaying downed dead wood, 100 years) is seen as the basis for the long carbon payback periods. The study results indicated a carbon payback period of 190 years for woody biomass from a boreal forest replacing coal in power plants (Holtsmark, 2011). The study used a larger area (landscape level) to determine the payback periods; in which the biomass regrowth and avoided emissions were important parameters. A study by Colnes et al., (2012) found that the atmospheric cumulative carbon balance is favourable after 35–50 years when utilizing forests in the South-eastern United States and thereby substituting different fossil fuel sources. Colnes et al., (2012) used a landscape-level approach in their cumulative atmospheric carbon balance. The study focussed on supplying current and potential future bioenergy projects with existing plantations.

The studies addressed above used different methodologies to assess the carbon debt pay-off period of bioenergy systems, compared with fossil-fuel reference systems. Next to the methodology (and methodological choices) the model input parameters are of influence as well, as discussed earlier. No studies were found that determined the carbon payback period and carbon parity point for fast-growing softwood plantations using different methodological approaches. The goal of this research is to establish carbon balances of wood pellet production in the South-east of the United States of America and subsequent cofiring in large-scale power plants, using stemwood (including thinnings) from softwood plantations, utilizing different methodologies. This case study will gain insight into the carbon payback time and carbon offset parity point of forestry biomass and methodological choices and issues related to forestry carbon balances. The case study analysis includes all major components of the carbon balance, including forest carbon pools, CO_2 equivalent emissions of silviculture practices, transportation emission and emissions related to pelletizing. The avoided fossil fuel emissions have also been taking into account. Given the increase in wood pellet demand in European countries we included an analysis of more intensive plantation management, including the related GHG emissions of silvicultural practices and the supply chain emissions.

As advocated by Searchinger et al., (2009), the greenhouse gas emission profile of bioenergy depends on the type of biomass feedstock used and land-use change effects caused by the land claim for feedstock production. The review of Johnson, (2009) showed that since 1992, numerous studies have been published on carbon accounting of bioenergy production systems. Schlamadinger & Marland have been used by IEA task 38 and the UNFCCC (2003). As early as 1996, Schlamadinger & Marland (1996) performed a carbon analysis of 16 bioenergy production system scenarios, varying from an ‘ethanol from corn’ scenario to ‘afforestation of agricultural land’ or a ‘continuing conventional forestry’ scenario. Schlamadinger & Marland (1996) found that with high growth rates and efficient use of harvested wood, the highest reduction in carbon emissions is with fossil fuel displacement. With lower growth rates or less efficient use of harvest material, the differences in final use (traditional forest products, bioenergy or no harvest) of the carbon balance is similar at a 100-year time frame. Forestry carbon pools include; soil carbon, tree carbon, other vegetation carbon, dead wood carbon and carbon in litter. Many different forest carbon accounting models exist, for example the FORCARB2 model (Heath, Nichols, Smith, & Mills, 2010), CO2FIX (Masera et al., 2003), EFISCEN (Nabuurs, Schelhaas, & Pussinen, 2000), GORCAM (Schlamadinger & Marland, 1996) and CBM-CFS3 (Kurz, Apps, Webb, & McNamee, 1992). The examples of carbon models pointed out here use forest inventories or empirical growth curves to determine forest carbon stocks (and subsequent carbon fluxes; Kurz et al., (2009)).

In recent studies different tools were used to determine the forestry carbon pools. Colnes et al., (2012) used the FVS-SN (Forest Vegetation Simulator-Southern Variant) to estimate the forest (re) growth and other forest carbon pools. The results are compared with the emissions of fossil fuels on a landscape level. McKechnie et al., (2011) adapted the FORCARB model to the regionspecific conditions for a temperate forest in Ontario, Canada. The results of this study were plotted as CO_2 pools, using a landscape-level approach. Mitchell et al., (2012) used also a landscape-level approach to show the impact of harvest intensity and rotation length on the carbon payback time and time before the carbon parity point is reached. The studies referred to here all used different harvest scenarios.

2.2 Materials and methods

In our study, the GORCAM carbon accounting model is utilized to determine carbon stocks and stock changes of forest carbon in softwood plantations in the South-eastern United States. An important feature of the GORCAM model is the ability to vary input parameters; to adjust the carbon accounting model to a region-specific case, while remaining user friendly at the same time. Among others, Schlamadinger & Marland (1996) and Zanchi et al., (2010) used the GORCAM model to determine forest carbon fluxes, including harvested carbon for bioenergy production. A detailed description of the GORCAM model structure and input parameter is shown in Schlamadinger & Marland (1996). Schlamadinger & Marland (1996) also provides an overview of 16 different bioenergy production systems and its carbon balance over time.

In our analysis, we determine the carbon balance of wholetree harvesting for wood pellet production, using different methodological approaches, under different management intensities. The stand-level, increasing stand-level and landscapelevel approaches are utilized for the different management intensity scenarios. This will gain insight into the potential effect of the different approaches. The intended results will show the carbon payback periods and carbon offset parity point of the different scenarios. All relevant input parameters for the GORCAM are shown as supplementary appendix.

A *stand-level approach* considers a 1 ha forest plot which is harvested completely at year 0, and harvested again at the end of the rotation period. In the results, the typical tree (re) growth curve is clearly depicted in the results using a stand-level approach. An *increasing stand-leve*l approach considers the harvest (and replant) of a forest plot each year. Important to note is that the carbon debt is considered at the harvest (and not at year 0), until the first harvested plot is harvested for the second time for bioenergy production. See Figure 2-2, a 25 ha plot with annual harvest; each year a new carbon debt is added to the total carbon debt. Therefore, utilizing an increasing stand-level approach, the carbon debt increases over time, until the next (consecutive) harvest. Considering a *landscape-level approach*, or a forest plot with uneven-aged (ranging in age from 0 to 25 years for low management intensity and 0–20 years for high management intensity) trees to enable annual harvest, the forest carbon pools are averaged (Berndes et al., 2011).

This would result in a stable ecosystem carbon level (assuming no change in forest management) throughout the modelling period, assuming an equal amount of forest plots compared with the years of one rotation.

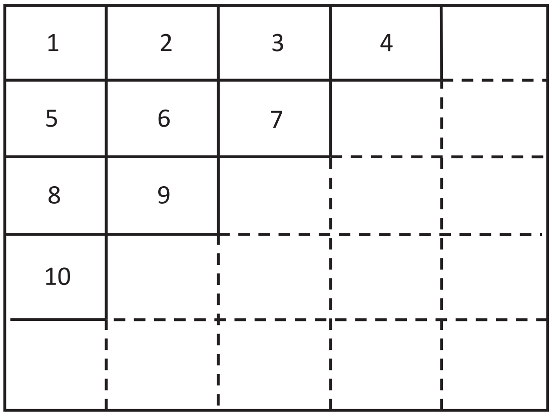

Figure 2-2 Increasing stand level approach, in this case after 10 harvests.

The plantation can be seen as part of the bioenergy supply chain, and therefore the whole supply area should be incorporated into the carbon balance. In other words, the plantation is part of the integrated supply chain. On the other hand, it can be argued that the plantations are independent to the wood pellet supply chain, and there is a choice for using it, (a) for energy, (b) for timber, pulp or other wood products or (c) not using them at all. We have developed a 'no-harvest' and a 'natural regrowth' scenario in which the plantations are not harvested or replanted after harvest; in this way, the softwood plantation could serve as carbon sink, a potential carbon mitigation strategy. These – to a certain extent hypothetical – scenarios are used when determining the carbon offset parity point. The 'no-harvest scenario' has the same starting point compared with the productive scenarios. Within both scenarios only the additional growth over the starting point (year 0 of modelling) is considered. The 'natural regrowth' scenario is developed to determine the carbon stock of a naturally regenerated forest plot; a longleaf pine forest plot (van Deuzen & Heath, 2011). All approaches used are expressed on a per hectare basis to allow easy comparison.

Case study

The states of Florida, Georgia, North Carolina, South Carolina and Virginia of the United States were selected as sourcing region for the case study. These states form the South-eastern United States of America and were considered to be representative of a potential sourcing region to supply the European wood pellet market. Forest land is a prominent land use in the South-eastern region of the United States. Of the Southern region, roughly 60% is categorized as forested land. More than 97% of the forested land is labelled as timberland. Areas qualifying as timber land are capable of producing in excess of 20 cubic feet per acre (1.40 m^3 ha^{-1}) per year of industrial wood in natural stands. In 2007, almost

86% of the timberland was privately owned; this category includes the forest industry, other corporate or individual and family owned forests (Smith et al., 2009). Of the area classified as timberland, 26% is stocked with loblolly-shortleaf pine and 12% is stocked with longleafslash pine. The age of softwood timber land is dominantly in the age class 0–19 years and 19–39 years of age, indicating recent clear-cut harvest.

A large fraction of the forested area in the Southern United States is actively managed to provide pulpwood, construction wood and other wood products. Southern forests provide around 18% of the global pulpwood and 7% of global industrial round wood demand, whereas Southern forest cover only 2% of the total forested area in the world (Hanson et al., 2010). Since 1950, the planted pine category increased from less than 1–7 million ha in 1999, largely at the expense of naturally regenerated pine (Wear & Greis, 2002). Both the ownership class and forest management type are indications of timberland ownership objectives, for example, planting is seen as an upfront investment for commercial wood production (Butler & Wear, 2013). In the Southern United States, Best Management Practices (BMP's) were developed to minimize the environmental impact of intensive harvesting and site preparation, for example, soil erosion and offsite movement of sediment (Fox, Jokela, & Allen, 2004). For example, in Georgia the latest version of the Georgian BMP was developed to 'establish sound, responsible, guiding principles for silviculture operations' (Georgia Forestry Commission, 2009). Despite the voluntary character of the BMP principles, compliance is high in Southern pine silviculture (Fox et al., 2004).

The GORCAM model is utilized to determine the forest carbon flows in South-eastern softwood plantations, where whole softwood trees are harvested for wood pellet production. The forest carbon modelling is extended with an inventory of fossil carbon emissions throughout the supply chain; including silvicultural emissions, transport emissions, pelletizing emissions and avoided fossil fuel emissions in the European power plants. The fossil-fuel reference system is coal fired power plants in North-western Europe. All carbon emissions in the supply chain are recalculated per scenario on a per hectare basis for the overall carbon balance and to enable comparison between scenarios.

In the South-eastern United States of America the potential to increase areal yields (Alavalapati et al., 2013) and the structural change in timber and paper and pulp demand (Wear & Greis, 2013) could support increased wood pellet production without land-use change. Therefore, the possible effect of direct and indirect land-use change is not taken into account. The wood pellets are produced from softwood plantations, which would otherwise be utilized for timber or paper and pulp production. When calculating the carbon balance, a carbon debt is taking into account. The carbon debt here is defined as the forest carbon stock affected by initial harvest, and is considered as a negative carbon flux. For the case study three different forest management scenarios were evaluated:

- The first scenario was the low management intensity scenario, with limited site preparation, planting and a clearcut harvest after 25 years.
- The second scenario included more intensive forest management practices in the softwood plantations: more intensive site preparation, planting, fertilization at age 3 and after thinning, a midrotation thinning at age 15 and clearcut harvest at age 25.
- The third scenario is the most intensive forest management. As the goal is to maximize annual yield, this scenario includes intensive site preparation, planting, fertilization around planting and at ages 5 and 12, herbicide application before planting, and at age 1. A thinning is performed at age 12, followed by a clear-cut harvest at age 20.

Both the softwood from thinnings and clear-cut harvest are used for wood pellet production. Input parameters for the GORCAM carbon accounting model are based on forest carbon inventory data, scientific publications, expert opinion and other relevant publications. Yield estimations are derived from Fox et al., (2004), Stantutf, Kellison, Broerman, & Jones (2003), Borders et al., (2004) and Kline & Coleman (2010). Greenhouse gas emissions of transport, silviculture emissions and pelletizing emissions are based on scientific publications, such as Markewitz (2006), Uasuf (2010), Sikkema (2010) and Magelli et al., (2009), and emission databases, such as the EcoInvent database.

Soil carbon

Soil carbon represents a large carbon pool in forestry. Important input for the soil carbon stock is the humification of downed dead vegetation. Removing (harvesting) residues is likely to reduce mineral carbon in soils, due to the reduced input from decomposing material (Peckham & Gower, 2011). As soil carbon stocks are not monitored, estimations are based on broad forest types (Ingerson, 2007). A review and metaanalysis of the effect of harvesting on carbon sequestration, described in Skog & Stanturf (2011), found that generally harvesting had no or little effect on soil carbon; whereas whole-tree removal showed a slight decrease in soil carbon. The meta-analysis of Nave et al., (2010) found that in temperate forests around the world harvesting reduces soil carbon on average, the variation was mainly caused by tree species, soil taxonomic order and time since harvest (recovery of carbon pools). Limited data were found on the soil carbon levels under different management intensities. Colnes et al., (2012) expected no significant changes in the soil carbon pool between the different end-use scenarios. Furthermore, Colnes et al. indicated the lack of accurate carbon models to model the soil carbon (change). In this research, the COLE (Carbon On Line Estimator; (van Deuzen & Heath, 2011) is used to gain insight into the soil carbon pools of softwood plantations. In case of reforestation the soil organic carbon value is constant, based on the assumption that soil carbon will remain constant over time (van Deuzen & Heath, 2011). Furthermore, the COLE database describes no soil carbon change due to higher management intensity (USDA, 2012). Based on this database and available literature (as described above) no soil carbon loss is assumed in our study, as stumps and harvesting residues are left on site. Even for a thinning; a silvicultural practice to yield biomass by removing every third (or fifth) row and off-size trees to enable further growth of the remaining trees, the tops and branches are left on site.

Truck transport

In this case study we assume an average distance from softwood plantation to wood pellet plant of 100 km (single trip). An emission factor for 16–32 tonne trucks was used (Spielmann, Dones, Bauer, & Tuchschmid, 2012). For empty return trips, emissions are reduced by 60% compared with loaded trucks (Hamelinck, Suurs, & Faaij, 2003). To express the GHG emissions as emission per tonne pellets, the amount of green tonnes transported per tonne of wood pellets needs to be determined. Throughout the supply chain, dry matter is lost during feedstock handling, pelletizing and during handling in export ports and during oceanic shipment (Sikkema, 2010). Consistent with Sikkema, a dry matter loss of 7% is assumed to account for the total dry matter loss in the supply chain from plantation to power plant. Next to dry matter loss, the feedstock required for drying also needs to be considered. In this case, it is assumed that 0.51 green tonnes of biomass (bark and wood shavings, assumed moisture content (MC) of 50%) are required for drying (similar to Uasuf (2010). This would result in a total biomass transport of 2.65 tonne roundwood/tonne pellets. Overall truck transport emissions to transport fresh roundwood to the wood pellet production facility are 62.33 kg CO_{2eq} per tonne pellets.

Pelletizing

The wood pellet production facility includes the debarking, chipping, drying, grinding and pelletization of the fresh softwood delivered at the plant gate. The debarking and chipping of roundwood is considered to consume 48 kWh per tonne pellets (Sikkema, 2010). During drying (heat is delivered by bark and wood shavings) the electricity consumption is assumed to be 39.67 kWh per tonne pellets (Uasuf, 2010). Other process steps like pelletizing, cooling and other miscellaneous electricity consumption account for 73.67 kWh per tonne pellets, 42.5 kWh per tonne pellets and 16.29 kWh per tonne pellets respectively. In the Southern United States, the emission factor for electricity is 729 g CO_{2eq} kWh^{-1}, including 6.5% transmission losses (EPA, 2012), resulting in a GHG emission profile of the pellet plant of 158.3 kg CO_{2eq} per tonne pellets.

International transport

Train

A train distance of 300 km is considered between pellet plant and international harbour, where large oceanic vessels can be loaded. This assumption is substantially lower compared to the 781, 750 and 900 km mentioned in the GHG analysis of Sikkema (2010), Magelli et al., (2009) and Uasuf (2010), as this case study setting is different. Within, on average, a distance of 300 km, a large forest supply area is available, therefore, a distance of 300 km is sufficient. The emission factor of train transport as specified by Magelli et al., (2009)is used to determine the GHG emissions related to train transport, this results in a GHG emission of 9.08 kg CO_2 per tonne pellets.

Oceanic transport

After port handling, the wood pellets are transported to the European mainland by large bulk ocean carriers. A travel distance of 7200 km is considered for transport from the Southeast of the United States to the Netherlands. The greenhouse gas emissions of oceanic transport are 0.0107 g CO_{2eq} per tonnekm. Taken into account a loss of 2% during wood pellet handling in the import harbour, the GHG emissions for oceanic transport are 92.4 kg CO_2 per tonne pellets.

Cofiring of wood pellets in Dutch power plants

The consumption of wood pellets for the production of electricity in Dutch power plants is calculated as 499 g of wood pellets per kWh electricity, based on a wood pellets lower heating value of 17.6 MJ kg^{-1} and a power plant conversion efficiency of 41% (Sikkema, 2010). When considering truck transport, pelletizing and international transport emissions, the overall GHG emissions for 100% wood pellet fired electricity is 161.78 g CO_{2eq} kWh^{-1}, excluding silvicultural emissions. Overall this would imply that every tonne of carbon harvested, assuming dry softwood contains 50% carbon (ECN, 2012), would in 1.56 tonne wood pellets and could produce 3.13 MWh electricity in Europe. With avoided emissions of 1081 kg CO_{2eq} MWh^{-1}, this would result in 3.38 kg CO_2 avoided, excluding supply chain emissions. For the carbon balances in section 2-3, a carbon replacement factor is determined. This factor represents the avoided carbon emissions per tonne of carbon harvested. In this case the carbon replacement factor is 0.923, resulting in 3.38 tonne avoided carbon dioxide emissions per tonne of harvested carbon.

2.3 Results

Productivity in Southern pine plantations

In the period between World War II and today, the productivity of Southern pine plantations has increased rapidly due to tree improvement programmes and silviculture management practices. Cooperation between governmental organizations, research and forest industry is considered to be the basis for this success (Fox et al., 2004). Figure 2-3 below gives an indication of the contribution of different forest management practices to the potential yield, and the decrease in rotation length of pulpwood plantations between 1940 and today in Southern pine plantations.

The potential to increase softwood yields in the South-eastern United States have been studied at large by different researchers. This section will highlight some of the relevant publications. Stantutf et al., (2003) published a detailed overview of potential yields of softwoods, including estimations of individual contribution of silviculture practices, from a researcher's perspective. The increase in productivity of high-intensively managed plantation compared with natural stands was also estimated by Stantutf et al., (2003). Most prominent factors were site preparation (21%), tree improvement (20%), fertilization (18%) and competing vegetation management (16%).

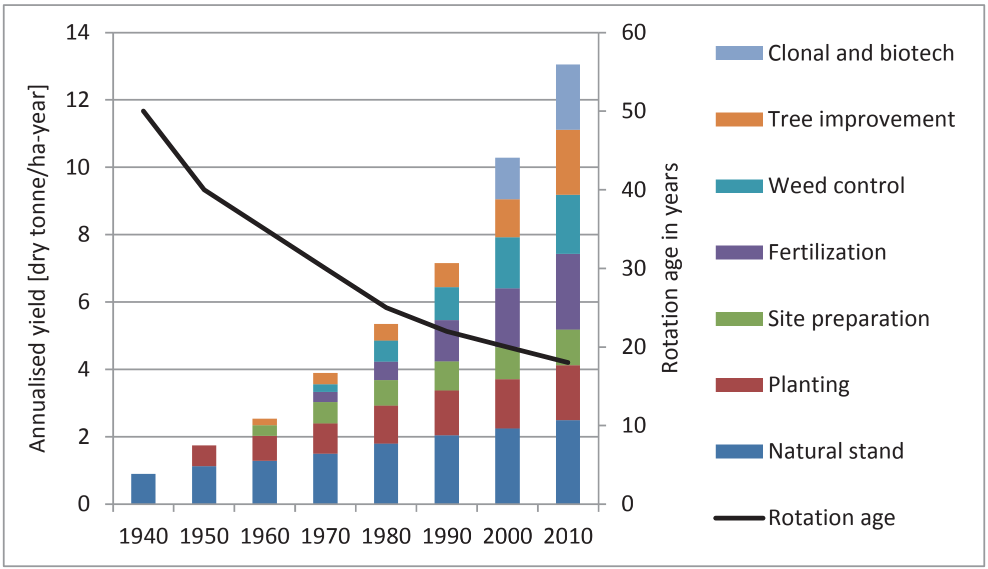

Figure 2-3 Estimated increase in upper limit yield, including indication of individual contribution, and rotation length in Southern pine plantations between 1940 and 2010, derived from (Fox et al., 2004).

An often quoted publication on potential softwood yields is that of Borders et al., (2004); which give the results of different forest plots subjective to different management regimes. As described by Borders et al., (2004), annual fertilization and competing vegetation control resulted in more than 180 Mg ha^{-1} at age 15; more than double the reference area without fertilization and vegetation control. This would correspond to roughly 12 Mg ha $^{-1}$ yr $^{-1}$, the upper level of the data presented in Figure 2-3. Aggregated interview responses of forest practitioners, as presented by Kline & Coleman (2010), estimated achievable yield of today's established plantations between 8 and 10 Mg ha $^{-1}$year^{-1}. Research plots are established to determine the practical yield response of the different silvicultural practices as the soil quality is also of influence (Vance, Maguire, & Jr, 2010). As a result of the increased forest management, the growth rate as well as the total stocking increased (Borders et al., 2004). A recent literature review of forest biomass yields was performed by (Vance et al., 2010). The potential yield increase is dependent on various elements: tree improvement, competing vegetation control, fertilization, site preparation before planting and tree planting to enable proper spacing. Pine seedlings have improved in recent decades by tree improvement programmes, traditionally focusing on seedling survival, increasing tree growth, disease resistance and wood quality (Vance et al., 2010). Site preparation provides seedlings with a jump start over other vegetation on site. It can include chopping, windrowing, burning, ripping, bedding, fertilization and herbicide application (Wear & Greis, 2002). After site preparation, pine seedlings can be planted mechanically or by hand. Fertilizer application in managed pine plantation during plant establishment (after thinning and midrotation) is becoming a common practice in the South (Wear & Greis, 2002). Soil nutrient availability, especially nitrogen and phosphorus, is an important growth-limiting factor in Southern pine plantations (Fox, Jokela, & Allen, 2007a; Jokela, Dougherty, & Martin, 2004). Control of competing vegetation is today mainly done by chemical treatment, thereby replacing prescribed burning to reduce competing vegetation in forest plots (Wear & Greis, 2002). Vegetation control can also be performed mechanically; this can include: anchor chaining, chopping, burning, root raking, shearing and disking (Fox et al., 2004).

The overall yield is set for the different scenarios based on the potential yield achievable under different forest management intensities. For the low-productive plantation, the overall yield after 25 years is 101 tonnes of dry biomass per hectare. A fertilized plantation, medium- productive plantation is assumed to yield in total (including midrotation thinning) 140 tonne dry biomass per hectare over a rotation period of 25 years. For the high-productive plantation the overall yield is 194 tonne dry biomass per hectare, in this case the rotation period is only 20 years. High management intensity is unlikely given the low demand for softwood pulpwood size material and the higher feedstock costs if cultivated under more intensive management compared with lower management intensity. We estimated feedstock production costs as 3.5, 5.6 and 7.6 € per dry tonne (based on the above described scenarios), excluding land use or land ownership fee or taxes and excluding harvesting and hauling costs.

Greenhouse gas emissions in the supply chain

The GHG emissions of the wood pellet supply chain consist of the emissions during biomass cultivation, harvesting, transport and conversion of raw feedstock to wood pellets.

Silviculture emissions

In this section, the GHG emissions during cultivation of fast-growing softwood species are presented. Silviculture emissions include the fossil fuel consumption of (a) forest management equipment used during planting, fertilizer application, herbicide applications, thinning and harvesting, (b) fertilizer and herbicide production and (c) N2O emissions from fertilizer application. The life-cycle emissions for seedling production are not taken into account due to data availability, but are likely to be small. The fossil fuel consumption of different silvicultural practices is given by Markewitz (2006). The total lifecycle emissions from fertilizer production are taken from LCA databases, excluding emissions after application. The N_2O emissions related to fertilizer application are determined by the IPCC methodology. See Tables 2-1 – 2-3 for a detailed overview of low-, medium- and highyield systems respectively. It includes the use of references and data concerning the carbon emissions of the different silvicultural practices under the low, medium and high management intensity scenarios respectively.

Important contributors to the carbon emissions during silvicultural practices are fertilizer production and applications, and diesel use during thinning and clearcut harvest. Therefore, there is a large difference between the emission factors of the low management intensity scenario and the medium and high management intensity scenarios.

After the cultivation phase (in this case, the cultivation phase also includes harvesting), the next elements are truck transport, pelletizing, international transport and cofiring in European power plants. Silviculture emissions, expressed as GHG emissions per kWh electricity, are 15.10, 38.86 and 47.70 g CO_{2eq} per kWh electricity for a low-, medium- and high-productive plantation respectively. Those values are extracted from Tables 2-1 – 2-3 above and include the dry matter loss of 7%. See Table 2-4 for an overview of GHG emissions of the wood pellet supply chain.

The goal of this section is to show the development of overall carbon balance for the three management intensity scenarios whereas the two different conceptual approaches: the stand-level approach and the landscape- level approach. The results are presented as cumulative carbon balances over 75 years. The following graphs include the carbon debt, silviculture emissions, supply chain emissions, tree and litter carbon and avoided fossil carbon emissions. Note that the emissions, carbon pools and avoided emissions are expressed as carbon equivalent and not as carbon dioxide (equivalent) which is commonly used in greenhouse gas calculations (1 tonne of carbon equals 3.67 tonnes of CO_2). As forest carbon pools are usually expressed as carbon pools, we used carbon equivalent as unit for the carbon balances.

Table 2-1 Low productive plantation carbon emissions and costs of silviculture practices, including harvesting emissions.

Year	Activity	Fuel / chemical consumption	Carbon emission per hectare [kg C/ha]
0	Raking and spot piling	43 litre fuel/ha[A]	39[B]
0	Planting (1600 trees/ha)[D]	28 litre fuel/ha[C]	26[B]
25	Harvesting	616 litre fuel/ha[E]	564[B]
			6.23 kg C/tonne dry biomass

Table 2-2 Medium productive plantation carbon emissions and costs of silviculture practices, including harvesting emissions.

Year	Activity	Fuel / chemical consumption	Carbon emission per hectare [kg C/ha]
0	Raking and spot piling	43 litre fuel/ha[A]	39[B]
0	Bedding	53 litre fuel/ha[F]	49[B]
0	Planting (1600 trees/ha[D])	28 litre fuel/ha[C]	26[B]
3	Fertilization	224 kg DAP/ha[G]	43[H]
3	Fertilizer application	9 litre fuel/ha[J]	31[J]

15	Thinning	616 litre fuel/ha[E]	564[B]
15	Fertilization	358 kg Urea/ha[G]	520[I]
15	Fertilizer application	9 litre fuel/ha[J]	31[J]
	N_2O emission N-fertilizer		377[K]
25	Clear cut harvest	616 litre fuel/ha[E]	564[B]
			16.03 kg C/tonne dry biomass

Table 2-3 High management intensity plantation carbon emissions and costs of silviculture practices, including harvesting emissions.

Year	Activity	Fuel / chemical consumption	Carbon emission per ha [kg Carbon/ per ha]
0	Raking and spot piling	43 litre fuel/ha[A]	39[B]
0	Bedding	53 litre fuel/ha[F]	49[B]
0	Herbicide	3.36 kg Velpar ULW/ha[L]	34[M]
0	Planting (1600 trees/ha[D])	28 litre fuel/ha[D]	26[B]
0	Planting stock		
0	Herbicide	11.2 kg Glyphosate/ha[L]	103[M]
0	Fertilization	224 kg DAP/ha[N]	43[H]
0	Fertilizer application	9 litre fuel/ha[J]	31[J]
1	Herbicide	11.2 kg Glyphosate/ha[L]	103[M]
5	Fertilization	140 kg DAP/ha[N]	27[H]
5	Fertilizer application	9 litre fuel/ha[J]	31[J]
5	Fertilization	431 kg Urea/ha[N]	625[I]
	N_2O emission N-fertilizer		418[K]
12	Thinning	616 litre fuel/ha[E]	564[B]
12	Fertilization	140 kg DAP/ha[N]	27[H]
12	Fertilization	431 kg Urea/ha[N]	625[I]
12	Fertilizer application	9 litre fuel/ha[J]	31[J]
	N_2O emission N-fertilizer		418[K]
20	Clear cut harvest	616 litre fuel/ha[E]	564[B]
			19.38 kg C/tonne dry biomass

[A] Fuel consumption of Caterpillar 525, 188 hp, for raking and spot piling: 43 litre/ha (Markewitz, 2006).

[B] GHG emission of diesel fuel: 0.916 kgCarbon/litre fuel (Hoefnagels et al., 2010).

[C] Fuel consumption of Caterpillar 525, 188 hp, with tree planter: 28 litre/ha (Markewitz, 2006).

[D] Planting density: 650 trees/acre, based on input data for life-cycle analysis

[E] Harvesting equipment fuel use: feller buncher, skidder and forwarder: 616 litre/ha (Markewitz, 2006).

[F] Fuel consumption of Caterpillar 525, 188 hp, with bedding plough: 52 litre/ha (Markewitz, 2006).

[G] Application rate diammonium phosphate and urea, based on input data for life-cycle analysis

[H] GHG emission DAP production based on phosphorus fertilizer production 710 gram CO_2eq/kg (Van Der Hilst et al., 2012).

[I] GHG emission urea production based on nitrogen production 5330 gram CO_2/kg (Van Der Hilst et al., 2012).

[J] Fertilizer application by helicopter: 9 litre fuel/ha: 31 kg Carbon/ha (Markewitz, 2006).

[K] Direct N2O emission of nitrogen fertilizer application according to IPCC guidelines, chapter 11 (IPCC, 2006).

[L] Herbicide application high intensity plantation (Markewitz, 2006).

[M] GHG emission herbicide production: 9.1 kg CO2/kg active ingredient, application emission 1.4 kg CO2/ha (Clair, Hillier, & Smith, 2008).

[N] Fertilizer application high intensity plantation (Markewitz, 2006).

Stand-level and increasing stand-level approach

In Figure 2-4, for the single stand-level approach, the carbon debt and cumulative (fossil fuel) emissions in the supply chain are presented as negative carbon pools (due to those emissions the atmospheric carbon increases). The forestry carbon pools presented here (tree carbon and litter) and avoided fossil fuel emissions are shown as positive carbon pools. The red line represents the balance of positive and negative carbon pools; where the line is below 0, this implies that at this point in time the total cumulative carbon emissions are higher than the avoided emissions. When the line crosses zero, initial net emissions have been 'paid back' by the regrowth of the plantation.

Another approach to determine the carbon payback is an increasing stand-level approach, as shown in Figure 2-5. As every year a plantation is harvested and used for wood pellet production, the carbon debt increases every year up to the point that a plantation is harvested a second time (after 25 years). As the tree carbon is only considered after the initial harvest, the total tree carbon pool is low in the first years, but sharply increases by year 25, due to both tree growth and an increasing forest plot. Emission of transport and pelletizing are directly linked to harvested biomass; therefore, the cumulative emissions of transport and pelletizing increase annually (due to annual harvest).

Table 2-4. GHG emissions of the wood pellet supply chain, expressed as CO_2eq/tonne of wood pellets

	kilogram CO_2eq/tonne pellets		
Silvicultural practices	30.27[A]	77.88[B]	95.61[C]
Truck transport	62.33		
Pelletizing[D]	160.47		
Train transport	9.08		
Oceanic transport	92.4		

	gram CO_2eq/kWh
Avoided GHG emissions [E]	1081

[A] Low productive plantation.
[B] Medium productive plantation
[C] High productive plantation
[D] In the US, the emission factor for electricity is 729 gram CO_2eq/kWh (EPA, 2012).
[E] The fossil fuel reference scenario is a pulverized coal fired power plant, operating in the Netherlands at an conversion efficiency of 41%. As specified by Koornneef, van Keulen, Faaij, & Turkenburg (2008) the direct and indirect GHG emissions totalling 1081 gram CO_{2eq}/kWh. This is in line with the fossil power reference as specified by Sikkema (2010).

Carbon payback periods for low-productive plantations

The results of a carbon balance for a low-productive plantation are shown in Figure 2-4 (top). In the first years (directly after the initial harvest), the avoided emission by fossil fuel substitution are lower than the carbon debt and fossil fuel emission in the supply chain. Due to tree (re) growth, with stable supply chain emissions, the carbon balance becomes positive after 11 years. Due to the high carbon replacement factor, a high fraction of harvested tree carbon turns into avoided fossil fuel carbon. As the carbon debt is constant, the carbon balance trend is increasing, with only minor relapse at harvesting.

Under the increasing stand-level approach, the carbon payback period of a low-productive scenario increases to 18 years, see Figure 2-5 (top). This is due to the fact that every year (up to year 25) the carbon debt of 1 ha is added to the total carbon debt. Simultaneously, an amount of fossil fuel carbon is replaced, followed by the regrowth of a plantation. As the carbon uptake of a plantation after replanting is low, the carbon payback period is extended compared with the even-aged stand-level approach.

Carbon payback periods for medium-productive plantations

The carbon balances of a medium-productive plantation, using a stand-level and increasing stand-level approach, are shown in Figure 2-4 and 2-5 (middle) respectively. The carbon pools are similar in both graphs. For both scenarios the carbon debt is set to 63 tonne carbon per ha. Compared with the low-productive scenario, the GHG emissions of silviculture, expressed in carbon equivalent, increased sharply, see Table 2-1 – 2-3. Despite that, the impact on the overall carbon balance is limited, as the increased yield more than compensates for the silvicultural emissions, see Figure 2-4. The carbon balance of the medium-productive scenario, using the standlevel approach, is positive after 7 years. Again an increasing trend was observed, following the trend of the softwood growth. Using the increasing stand-level approach for the medium-productive plantation scenario the payback period increases to 13 years, see Figure 2-5 (middle). Also in this approach the increasing cumulative fossil fuel emissions in the supply chain are counteracted by the cumulative fossil fuel displacement for the improved yields.

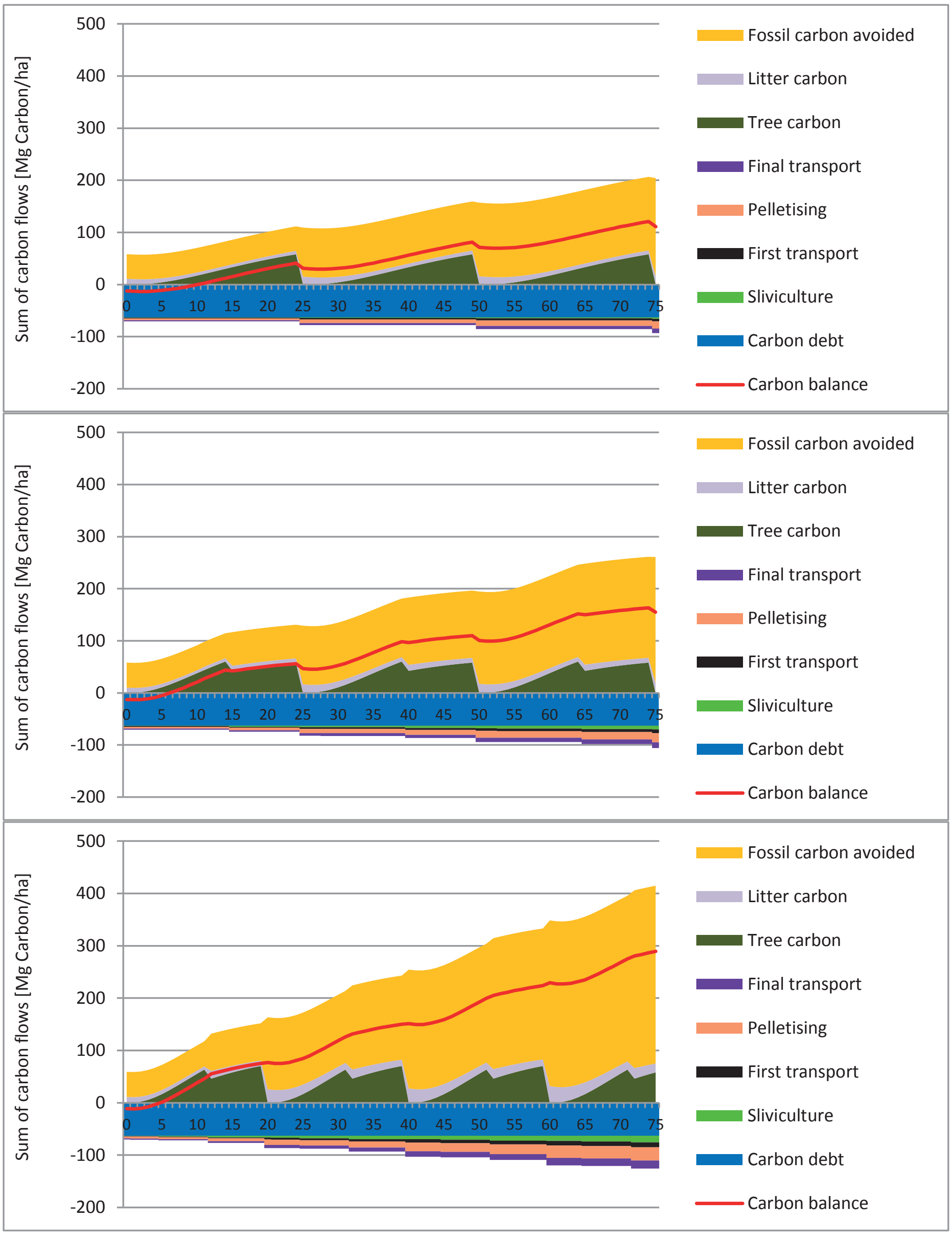

Figure 2-4 Carbon balance of 1 ha for a low- (top), medium- (middle) and high (bottom) productive plantation, including emissions in supply chain and avoided coal emissions, utilizing a stand level approach.

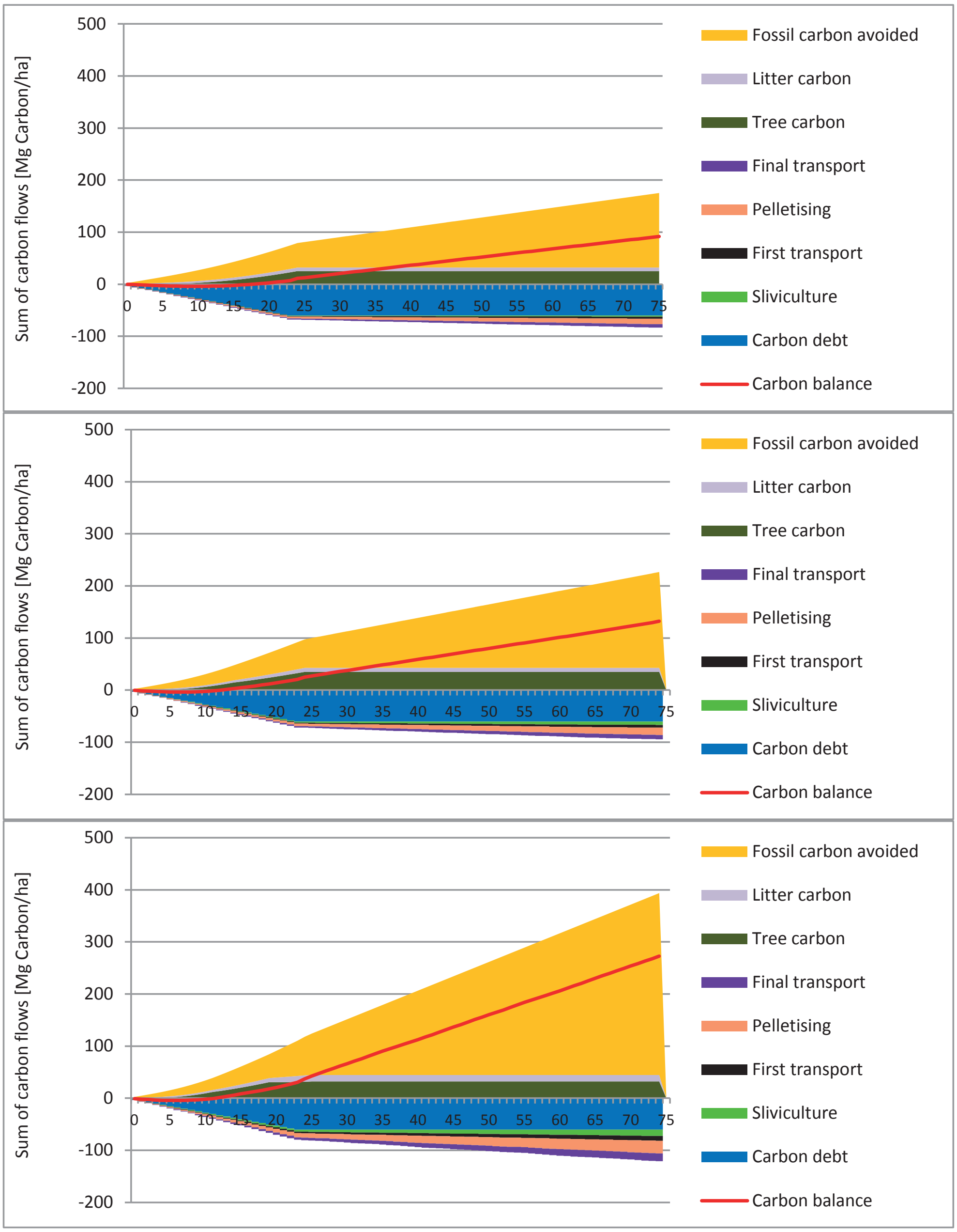

Figure 2-5 Carbon balance of 25 ha for a low- (top), medium- (middle) and high (low) productive plantation (expressed on an average per hectare basis), including emissions in supply chain and avoided coal emissions, using an increasing stand level approach.

Carbon payback periods for high-productive plantations

In Figure 2-4 (bottom) the carbon balance of a high-productive softwood plantation is shown. The high yield is a result of intensive forest management on high-quality seedlings, which increase silviculture emissions. Due to higher management intensity, the growth rate is higher compared with the low-productive scenario, the rotation period is therefore set to 20 years. The midrotation thinning is at age 12.

Using the stand-level approach, the carbon payback period is reduced to 5 years after the initial harvest. The carbon debt is repaid fast due to the high growth rate. As a result of this high growth rate the carbon balance trend is steeper compared with the low- and medium productive plantations. The higher yield more than compensates for the higher emissions of silvicultural practices.

Carbon payback period for the landscape-level approach

A different approach to depict the carbon balance of softwood plantations is the use of a landscape-level approach, as discussed in the methodology section (section 2-2). In this analysis, the carbon balance with the landscape approach is depicted as the amount of carbon on 1 hectare. The landscape-level approach takes into account both the creation of a carbon debt, and at the same time the carbon uptake of the not-harvested area that year. In this way, the overall carbon stock of the area remains stable, as harvested carbon is less or equal to biomass (re) growth. The carbon balances of a low-, medium- and high-productive scenario are presented in Figure 2-6 respectively. In the results, the carbon debt represents the average carbon debt of an uneven-aged plantations (ranging in the age from 0 to 25 years old). Every year, a carbon debt is created on a hectare, but this debt is basically directly compensated by the uptake on the 24 (or 19) other hectares within the plantation area. Due to this, the carbon payback period is reduced to less than 1 year; as in this case the carbon debt is similar to the carbon stock of the softwood plantation. When considering the landscape level all 25 ha are incorporated in the total supply chain. As in this analysis the forest growth equals the initial carbon debt, the carbon payback period is 1 year. In Figure 2-6 the avoided carbon emissions of the different forest management intensity scenarios are clear; in the longer term the high-intensive scenario avoids the most fossil fuel carbon emissions.

Carbon offset parity point for productive scenarios

As shown in the previous section, when considering a landscape-level approach, carbon payback times become basically negligible (i.e. shorter than 1 year) even under the low-productive scenario. To determine a carbon offset parity point, the carbon balances are compared with a ‘no-harvest’ scenario. In this scenario, the existing plantations are not harvested for wood pellet production or any other purpose. In this way, the softwood plantations could in theory serve as a carbon sink, a potential carbon mitigation strategy. Note, however, that after a certain amount of time, the uptake of carbon diminishes, and finally comes to halt as the plantation reaches an equilibrium state between growth and decay. Also, given the presence of the wood processing industry and upfront investments to enhance productivity in the South-eastern softwood plantations, not using softwood plantations on a large scale is considered unlikely, unless this method is seen as carbon mitigation strategy and land owners are (financially) reimbursed for not harvesting their trees.

In Figure 2-7, the carbon balances of the three scenarios, expressed in the increasing stand-level approach, are compared with the carbon balance of nonharvested softwood plantation. For the three productive scenarios, only the overall carbon balances are shown. Next to those lines, the tree and litter carbon increase in an unharvested plantation is considered, this plantation differs in age between 0 and 24 years. Note that only the additional growth is shown; the base line is a 25- year-old softwood plantation. Not harvesting is favourable from a carbon balance point of view, until years 17, 22 and 39 for the high-, medium- and low-productive scenario respectively. In other words; the carbon offset parity point is at 17, 22 and 39, for the three scenarios. After the break-even point, use for wood pellet production is preferred over the nonharvest scenario from a greenhouse gas point of view. It is also clear that the absolute size of the temporary negative carbon balance is limited, whereas the positive carbon balance after break-even soon reaches levels many times greater. Using the increasing stand-level approach the carbon balance of the productive scenarios is more than double, triple or almost seven times greater compared with the ‘no-harvest’ scenario, after 75 years. Applying the landscape approach the difference is a factor 1.7, 2.3 or 3.8, for the low-productive, medium-productive and high management intensity scenario, respectively, see Figure 2-8.

Similarly, in Figure 2-8, the carbon balances of the different scenarios are compared with a ‘no-harvest scenario’ using a landscape approach. The carbon parity point is at year 12, 27 and 46 for the high-, medium- and lowproductive scenario, see Figure 2-8. For the high-productive scenario the carbon offset parity point is shorter using the landscape-level approach compared with the increasing stand-level approach. On the other hand, the low-productive scenario results in higher carbon offset parity points when comparing the two approaches.

This can be explained by the typical S-shaped tree growth curve, especially presented in the curve for tree and litter carbon for the ‘no-harvest scenario’. In this analysis a S-shape growth curve is considered for softwood growth, therefore, within the ‘no-harvest scenario’ the additional growth diminishes.

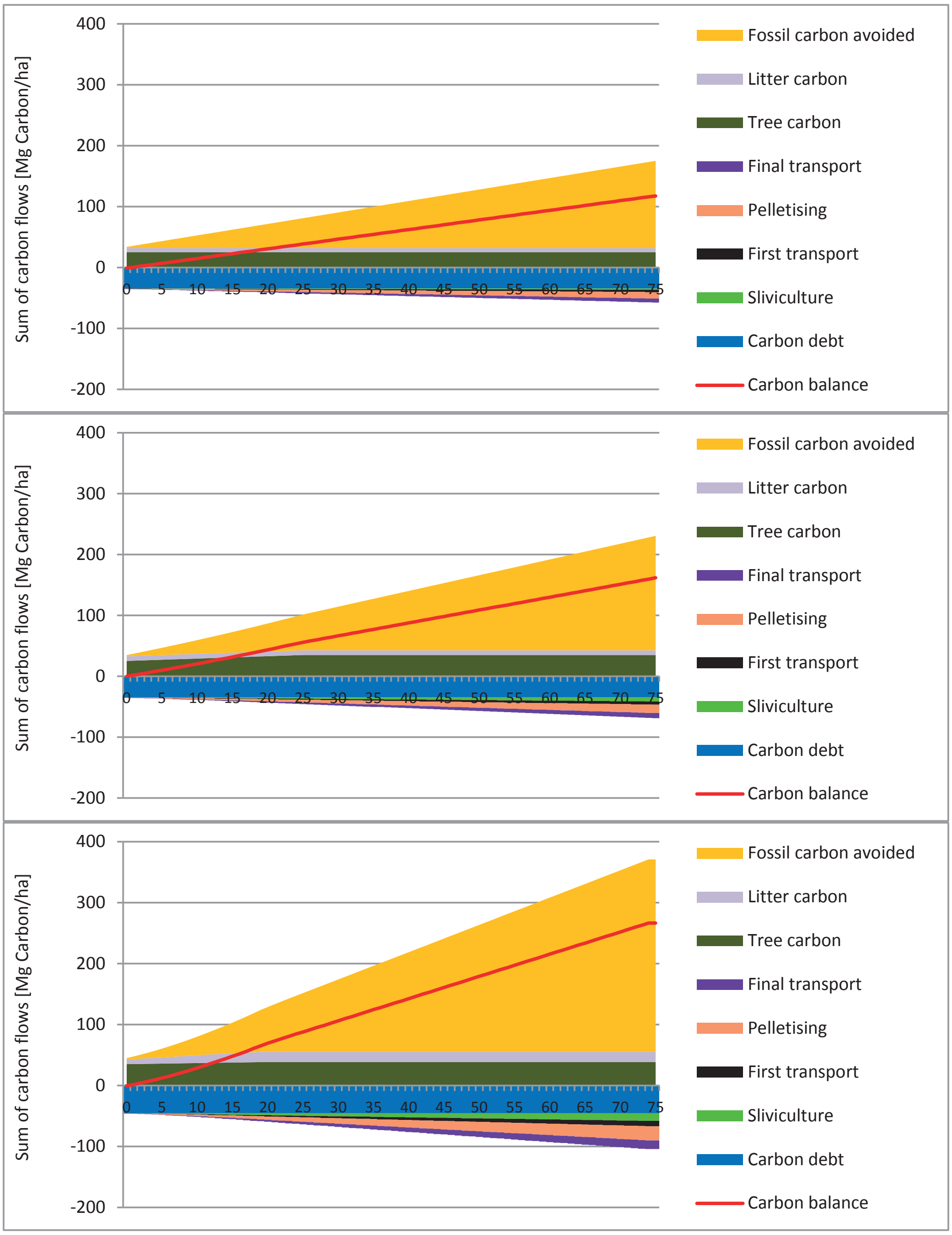

Figure 2-6 Carbon balance of 1 ha for a low- (top), medium- (middle) and high (bottom) productive plantation, including emissions in supply chain and avoided coal emissions, using an landscape approach.

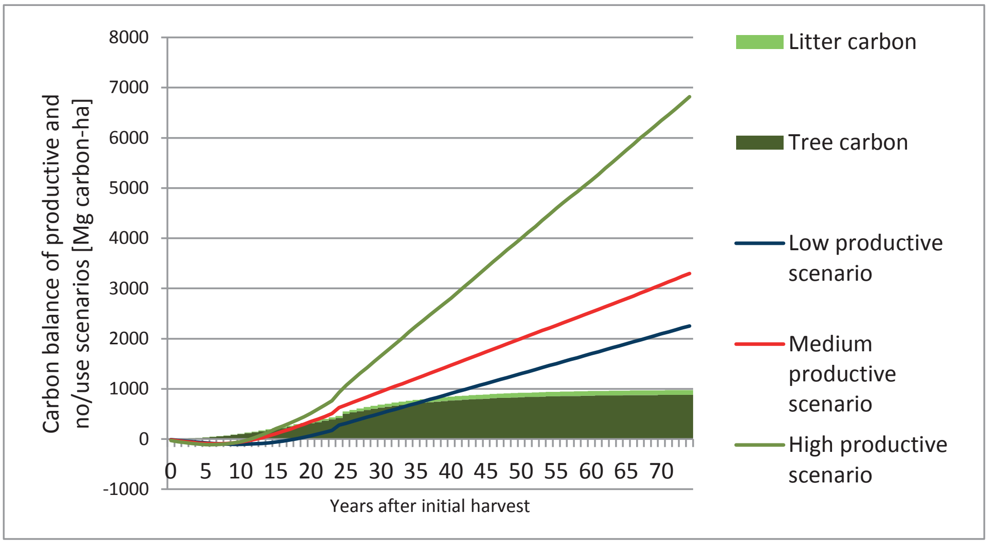

Figure 2-7 Carbon balances of productive scenarios compared to a no-harvest scenario, using an increasing stand level approach.

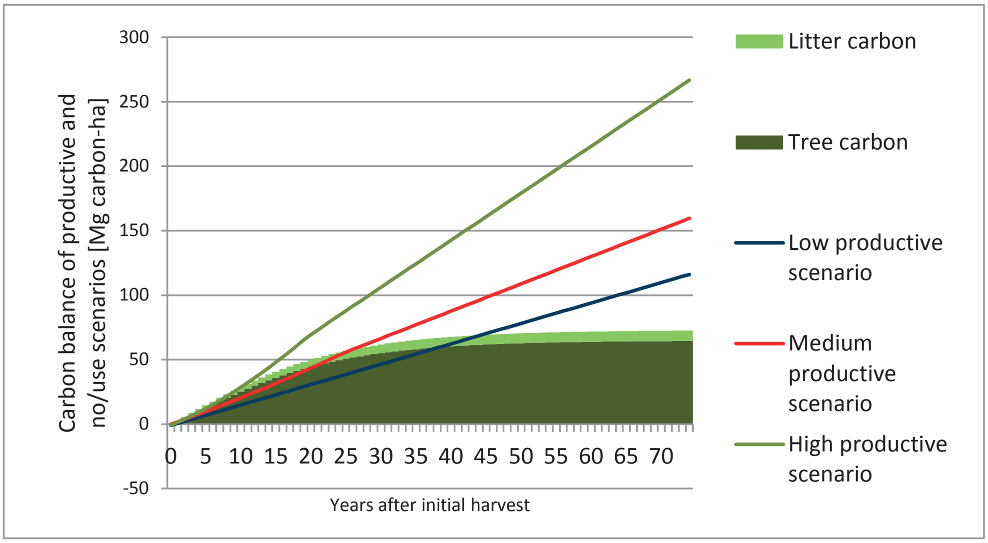

Figure 2-8 Carbon balances of productive scenarios compared to a no-harvest scenario, using a landscape level approach.

Table 2-5 Carbon payback time (stand level approach) and carbon parity point (landscape level approach) for the low-, medium- and high management intensity levels. The bold values are used in Figures 2-4 to 2-8 .

Electrical efficiency power plant	**Gram CO_2eq/kWh avoided emissions**	**Carbon payback time in years (stand level)**	**Carbon parity point in years (landscape level) no harvest**	**Carbon parity point in years (landscape level) no replanting**
35%	713	27^A / 16^A / 8	106 / 68 / 39	91 / 59 / 15
	1081	13 / 8 / 6	57 / 37 / 17	46 / 7 / 4
41%	713	22^A / 10 / 8	80 / 55 / 28	72 / 41 / 9
	1081	11 / 7 / 5	46 / 27 / 12	30 / 3 / 3
46%	713	15 / 9 / 7	69 / 46 / 21	60 / 25 / 6
	1081	8 / 5 / 4	39 / 21 / 8	6 / 2 / 2

The carbon balances presented thus far have been calculated that the wood pellets are cofired in an average Dutch coal power plant (41% efficiency) and that electricity from coal is replaced. In Table 2-5, an overview is given for the carbon payback period (stand level) and the time until carbon parity point is reached (landscape level) using also different electrical conversion efficiencies for the (coal) power plant in which the biomass is (co) combusted, and the emissions of the reference power plant. The absolute difference carbon balances of the productive scenarios and the no-harvest scenario are small, especially in the short term, see Figures 2-7 – 2-9. As a result of that a small difference in the case study input parameters could have a large effect on the carbon parity point. Or the carbon parity point is reached quickly or after the carbon balance of the reference scenario stabilizes.

Figure 2-9 shows the carbon parity point of the three productive scenarios compared with a ‘natural regrowth’ scenario. Such a scenario could occur when land owners do not expect any future markets for round wood (neither for material nor energy purposes), and thus abandon their plots after the current harvest. Under such circumstances, natural regrowth would occur, resulting in significantly slower carbon uptake compared even with low-management plantations. Under such an alternative reference scenario, carbon payback and parity times are shortened to 8–33 years.

Impact on GHG saving potential

In the previous section, we have illustrated various carbon balances over time. To actually quantify GHG savings, it is necessary to choose a time horizon, e.g. GHG savings within the next 20 years. The results of greenhouse gas accounting in biomass production can also be calculated according to this methodology, similar to the EU methodology for GHG accounting EC European Commission (2010).

The EU methodology takes into account the carbon stock change between the initial carbon stock and the carbon stock when the energy crop matures, with a maximum of 20 years after the initial harvest or conversion of land into plantation. This is depicted as the carbon stock change bar in Figure 2-10. Note that in the case of switching from a low- to high-productive plantation, the carbon stock after 20 years is actually higher than in the initial state, resulting in a negative emission.

Next to the carbon stock change, the supply chain emissions are incorporated as well, identical to the other approaches described above. The overall emissions are compared with a general fossil fuel comparator (198 g CO_{2eq} per MJ electricity). In Figure 2-10, the overall emissions of wood pellets are presented. The silviculture and supply chain emissions and carbon stock change emissions are expressed as carbon dioxide equivalent per MJ electricity. The supply chain emissions (truck, pelletizing, train and oceanic transport emissions) are identical for all scenarios. The carbon stock change is the difference between the carbon stock before initial harvest or land-use change, compared with the carbon stock of the land in use before biomass production. In this case the carbon stock of the actual land use is the carbon stock after 20 years, as forestry biomass accumulates over more than 1 year, and softwood trees reach maturity after more than 20 years. The carbon stock change is recalculated to CO_{2eq} emissions per MJ electricity, including the conversion of harvested tree carbon into wood pellets output, dry matter losses in the supply chain and power production efficiency. In our analysis the carbon stock change is defined as the difference between the carbon stock of a mature (25 years old) low-productive softwood plantation and the carbon stock after 20 years of initial harvest. This analysis shows that the carbon stock change is an important element of the overall GHG emission profile of wood pellet fired electricity. It could double the overall GHG emission footprint or reduce the emission profile to zero, see the net emission, represented by the red dots in Figure 2-10. Seen from a GHG emission profile, determined according to the above described methodology, the high management intensity scenario is favourable over the medium- and low-productive scenario. However, this result only applies for the first harvest, as subsequent harvests would not show any further carbon stock depletion if the harvesting frequency remains constant. Therefore, these results do not apply for second- or third-generation forest plantations.

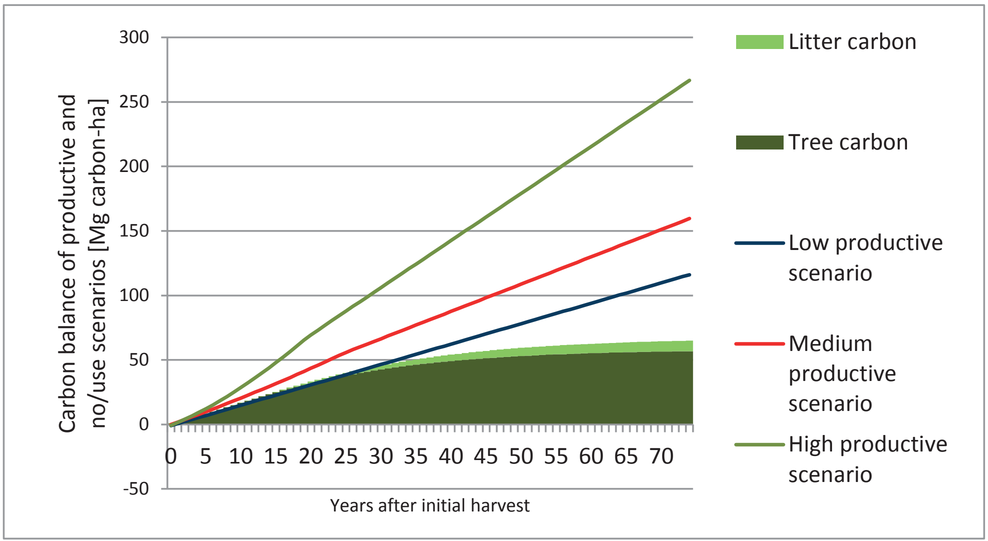

Figure 2-9 Carbon balances of productive scenarios compared to a no-replanting scenario, using a landscape level approach.

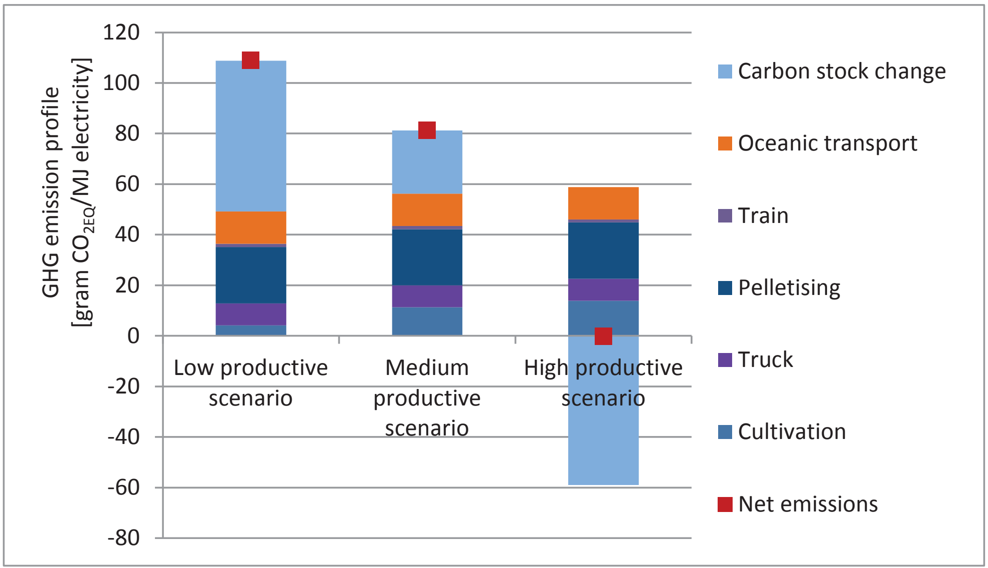

Figure 2-10 Average GHG gas emission profile of wood pellet fired electricity, expressed as CO_{2eq}/MJ electricity, for the low-, medium- and high productive plantation scenario of the first harvest.

2.4 Discussion and conclusion

The result of the carbon balances clearly demonstrate that the choice of carbon accounting method has a significant impact on the carbon payback and carbon offset parity point calculations. When only looking at the carbon debt a landscape level, the time spans to reach break-even point become negligible, i.e. shorter than 1 year.

However, most other studies Colnes et al., (2012); Mitchell et al., (2012); Walker, Cardellichio, et al., (2010); Zanchi et al., (2010) use the carbon offset parity point method. When comparing our results with these studies, we find that the carbon offset parity point is reached after 17, 22 and 39 years for the increasing stand-level approach. Applying the landscape approach, the carbon offset parity point is reached after 12, 27 and 46 years, for the high-, medium- and low-productive scenario. These times are shorter than the time spans identified by the studies cited above, which find carbon payback periods of <1 year for wood pellet production on former agricultural land (Mitchell et al., 2012; Zanchi et al., 2010), between 16 and 90 years on forested land Walker, et al., (2010); McKechnie et al., (2011) and 19 to 1000 years for old-growth forests (Mitchell et al., 2012; Zanchi et al., 2010). Both the methodology used and data input are of major importance. In our analysis, the data input is region specific; especially on the carbon stocks and growth curves of softwood plantations in the Southeastern United States softwood plantations. Next to this we identify the following reasons for the differences:

- The carbon debt considered is of a mature softwood plantation in a (subtropical) climate, as compared with old-growth (boreal) forests in equilibrium, which are used in other studies (Mitchell et al., 2012; Zanchi et al., 2010). In our case study, the growth rate of softwood is high compared with hardwood species or boreal (unmanaged) forests. Therefore, the carbon debt is repaid rapidly by the regrowth of the plantation.
- Some scenarios presented (e.g. Mitchell et al., 2012; Zanchi et al., 2010) assume significant soil carbon loss, when old-growth forests are converted into plantations. Typically, the pine plantations considered in our study were established decades ago. During harvest residues are left on site, thereby making the probability of soil carbon loss relatively low. Thus, we assume no soil carbon change, which is also in line with (Colnes et al., 2012). We point out that no data on soil carbon changes under different management intensities were available. We agree with Skog & Stanturf, (2011), who point out that more research is needed to identify forest types, and soil combinations were potential soil carbon loss could be triggered. In comparison, Zanchi et al., (2010) considered a high carbon debt, as in this scenario harvesting residues were removed.
- Total amounts of carbon stored in old-growth forests (as assumed, e.g. by Zanchi et al., (2010)) are typically much higher than in the pine plantations we use. For example, Zanchi et al., (2010) assume in a worst case scenario an initial carbon debt of 275 tonne C ha $^{-1}$. For comparison, such carbon levels are only found in our study area in mature swamps, including both soil and nonsoil. As such areas are also strictly protected, it is not possible to incur such high carbon debts in our study area. However, if (hypothetically) this would be possible, the carbon

payback period in our case study would increase to 55–132 years for a stand-level approach, compared to 150–200 years found by Zanchi et al., (2010).

- The efficient supply chain and high fossil fuel carbon replacement is of large influence. The carbon replacement factor (or carbon efficiency) is high in this case study; 0.92 tonne of fossil fuel carbon is replaced by 1 tonne of harvested (biomass) carbon. Mitchell et al., (2012) used a carbon replacement factor of 0.51. This is due to the fact that he considers the avoided carbon emissions and supply chain emissions at the same time, assumes a rather low biomass conversion efficiency and assumes that biomass replaces a fossil fuel mix instead of solely replacing coal. As wood pellets directly replace coal in our case study, a 0.92 replacement factor seems justified.

Finally, we point out that in our case study, the choice of 'no-harvest' as reference scenario for the parity offset point calculations is not straightforward. From interviews with forest experts in South-eastern United States, we consider 'no-harvest' and 'natural regrowth' scenarios as not realistic; without financial compensation it is likely that plantations that are not harvested for timber/ fibre would be converted into, for example, urban development or agricultural land. In such a case, no or significantly less carbon would be fixed in the reference scenario, which would then most likely be far worse than any bioenergy scenario.

Using the stand-level approach, the carbon payback period of a single stand varies between 5 and 11 years, dependent on the management intensity scenario. For the carbon offset parity point, using the increasing stand-level approach, the productive scenarios are preferred after 17–39 years. For the landscape approach, the range is even wider: from a 46 years carbon offset parity period in the worst case, to a mere 12 years for a high-intensity scenario. The input parameters are case study specific and methodology dependent; therefore, the results are case study specific as well, and can differ substantially between cases. We conclude that:

- Forest carbon accounting models are important for a better understanding of carbon stock change over time, essential parameters are (annualized) yields, carbon replacement factor and initial carbon stock (carbon stock change due to management or landuse change). The choice of methodological approach has a large impact on the calculations of carbon payback period or carbon offset parity point.
- When the 'no-harvest' scenario is compared with the bioenergy scenarios, we conclude that initially, the carbon balance of the 'no-harvest' scenario is more favourable. However, after the carbon offset parity points (see above) the bioenergy scenarios are favourable. Therefore, apart from the question how realistic no-harvest or natural regrowth scenarios are (i.e. what the economic implications of such scenario would be), not utilizing softwood plantations for wood pellet production is not a viable pathway to structurally reduce GHG emissions on the longer term.

- This analysis points out that switching to highly productive plantations (only if sustainably managed) increases the uptake of carbon strongly, which offsets the additional emissions of silvicultural practices by far. Increased silvicultural emissions are compensated by faster (re) growth of plantations, and thereby increased uptake of carbon and increased fossil fuel displacement. However, given the low current softwood stumpage prices (a result of ample supply), it is expected that this scenario is not executed currently at large scale by land owners as silvicultural costs are higher for higher management intensities.
- The results show that the time before the carbon debt is repaid or time before the carbon offset parity point is reached strongly varies on (a) the management system and (b) the methodological choices. We consider the landscape-level carbon debt approach more appropriate for the situation in the South-eastern United States, where softwood plantation are already in existence, and under this precondition, we conclude that the issue of carbon payback is basically nonexistent. Assuming that coal is directly replaced in an average coal power plant, the carbon offset parity point (compared with noharvest scenario), however, is in the range 12– 46 years; i.e. one or two rotations. The absolute difference in avoided carbon emissions before the carbon offset parity point is relatively small in our case study, the benefits gained after the parity points is reached, however, are substantial.

Carbon balances of forestry biomass are case study specific (region and forest type), therefore we would suggest to utilize carbon accounting models to other locations, with its own specific characteristics. The data availability for soil carbon data is an issue; more research is needed on where soil carbon loss can be triggered.

Acknowledgements
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Supplementary information

Input parameters for GORCAM carbon accounting model

		Low management intensity	Medium management intensity	High management intensity	Natural re-growth
	Time period [year]	100			
	Time step [year]	1			
Biomass (vegetation)	Initial carbon debt [tC/ha]	-63 tonne C/ha			Not relevant
	First rotation [yrs]	25	25	20	Not relevant
	Maximum standing stock [tC/ha]	90	120	150	73
	Carbon at the beginning of each rotation [tC/ha]	0	0	0	0
	Initial relative growth rate [1/yr]	0.08	0.108	0.12	0.07
	Parameter can be used to move the point of inflection of the growth curve	-0.36			
Biomass (soil and litter)	Time until the production of herbaceous and fine root litter reaches 90% of ist maximum [yrs]	75			
	standing stock of the crop [tC/ha-yr]	1.00			
	Stem litter pool size at time t=0 [tC/ha]	0.00			
	Decay rate for stem litter [1/yr]	0.07			
	percent of harvest to floor_stem, init. [%]	15%			Not relevant
	percent of harvest to floor_stem [%]	15%			Not relevant
	percent of thinning to floor_stem [%]	15%			Not relevant

Growth curve	Vegetation growth curve	Richards function with thinning	
Soil and litter	Soil and litter	dynamic (s/l displayed separately)	
Human intervention	Percent of init. harvest for fuel [%]	85%	Not relevant
	Percent of harvest for fuel [%]	85%	Not relevant
	Percent of thinning for fuel [%]	85%	Not relevant

Chapter 3

Carbon balances and economic performance of pine plantations for bioenergy production in the Southeastern United States

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In preparation

Abstract

The management strategies of loblolly pine (*Pinus taeda*) plantations in the Southeastern USA can be adapted to fulfil both the demand for wood products and for bioenergy. This study quantifies the impact of plantation management choices on the carbon balance and economic performance of bioenergy production using loblolly pine in the Southeastern USA. It calculates the cumulative carbon balance and the net present value of a 1 ha loblolly pine plantation), and wood supply cost for bioenergy production for different management strategies. The strategies assessed (conventional, additional thinning and short rotation), are characterised by planting density, thinning age and rotation period, each with and without collection and utilization of slash residues for bioenergy. The total wood supply costs for bioenergy include the cultivation, harvesting and transport costs for small diameter trees and slash. The results show that the carbon balance after 100 years is 205 (247), 214 (268) and 149 (195) Mg ha^{-1} for the conventional, additional thinning, and short rotation loblolly pine plantation management strategies (within parentheses: same strategies but with slash wood). The conventional strategy has the lowest wood supply costs for bioenergy, 47 (46) \$ Mg^{-1} pulpwood, followed by the additional thinning strategy, 50 (49) \$ Mg^{-1} pulpwood, and 54 (52) \$ Mg^{-1} pulpwood for the short rotation management strategy. In conclusion, switching from the current conventional strategy without the use of slash for bioenergy to an additional thinning strategy with the use of slash increases the overall carbon accumulation by about 31 %, at marginally higher wood supply cost. increased plantation management can have a positive effect on the economic performance and on the carbon balance of loblolly pine plantations. Integration of woody bioenergy use and traditional forestry sectors leads to co-benefits in terms of cost reduction and carbon accumulation.

3.1 Introduction

The increase in atmospheric anthropogenic greenhouse gasses (GHG) is considered to be the key driver of human induced climate change (Pachauri, 2014). The utilization of bioenergy, potentially in combination with CO_2 capture and storage, is considered as an important GHG emission mitigation option (H. Chum et al., 2011; Pachauri, 2014). Softwood plantations in the Southeastern United States of America (USA) are recognized as potential biomass feedstock to meet the domestic as well as transatlantic demand for bioenergy (Dwivedi, Johnson, et al., 2016; Goh et al., 2013; Perlack & Stokes, 2011). Currently, harvested softwood is used to produce a variety of timber products in the Southeastern USA, including sawtimber, pulpwood, veneer logs, plywood, industrial fuel, and other wood products (Oswalt et al., 2014). With an increasing interest in fossil displacement, there is a growing potential demand for (low-cost) biomass feedstock. Today, a common softwood management strategy in the Southeastern USA is tailored to produce a mix of sawtimber- and pulpwood-size wood in a rotation period of around 25 years (Perlack & Stokes, 2011). Harvested softwood in the South is classified according to the minimal diameter of the tree at breast height (d.b.h.) and the minimal top diameter. Commonly, three main wood classes are distinguished, from small to larger diameters; pulpwood (PW), chip-n-saw (CNS) and sawtimber (ST) size wood. Bark and lignin is already used for energy in wood processing facilities. For large-scale bioenergy production smaller trees, trees not suitable for wood products and harvesting residues are being proposed, or already used for bioenergy (Perlack & Stokes, 2011). Plantation management strategies can be altered to maximise the production of bioenergy feedstock. This may include increased planting density, additional thinning and/or shortening the rotation period to increase annualised wood production per hectare (Perlack & Stokes, 2011; Scott & Tiarks, 2008). However, changes to the plantation management for the enhanced production of bioenergy from forest biomass has raised concerns over the loss of carbon stocks and the temporal imbalance between carbon release and uptake (Lamers & Junginger, 2013). Furthermore, adapting the plantation management strategy may result in higher cultivation and/or harvestings costs (Perlack & Stokes, 2011). Given the existing wood industry in the Southeastern USA, the anticipated increased harvests for bioenergy production in the Southeastern USA face a number of challenges that may limit the production of bioenergy. First, the utilization of forest plantations for bioenergy should provide a net reduction in GHG emissions compared to the alternative scenario. Second, the total bioenergy production should be economically compatible with other (renewable) energy sources and other land uses.

The use of softwood, especially the native loblolly pine (*Pinus taeda L.*), in commercial wood plantations in the Southeastern USA is often justified by forest practitioners by emphasizing the high yield of merchantable wood on a wide range of sites (Kline & Coleman, 2010). Loblolly pine yield is very responsive to plantation management practices, the impact on diameter growth rate and biomass accumulation in the Southeastern USA is widely reported (Albaugh, Lee Allen, Dougherty, & Johnsen, 2004; Fox, Jokela, & Allen, 2007b; Jokela et al., 2004; Samuelson, Johnsen, & Stokes, 2004). The impact of softwood plantation management choices (e.g. fertilization or planting density) also impacts the merchantable volume of sawtimber, chip-n-saw and pulpwood, as discussed by various publications, e.g. (Dickens & Will, 2004; Dwivedi & Khanna, 2015; Munsell & Fox, 2010; Straka, 2014; Sunday, Dickens, & Moorhead, 2014; Vance et al., 2010). The carbon uptake by tree growth, sequestration in wood products and carbon displacement by material substitution is reported by various publications, among others; (C.a. Gonzalez-Benecke et al., 2015; Carlos a. Gonzalez-Benecke, Martin, Cropper, & Bracho, 2010; Carlos a. Gonzalez-Benecke, Martin, Jokela, & Torre, 2011; Upton, Miner, Spinney, & Heath, 2008). Furthermore, the impact of wood utilization (including bioenergy) on the carbon accumulation is discussed in other studies, e.g. (Holtsmark, 2011; Jan Gerrit Geurt Jonker, Junginger, & Faaij, 2014; Lamers & Junginger, 2013; Mitchell et al., 2012; Upton et al., 2008).

As illustrated by Dwivedi and Khanna (2015) the optimal rotation period to maximise economic profit is defined by the site quality and plantation management intensity. Dickens and Will (2004) concluded that increasing planting density may increase wood yield, however, the disparity in price between pulpwood, chip-n-saw, and sawtimber suggests there is an optimal planting density to maximise net benefit. A high planting density with additional thinning is only economically viable if harvested trees reach merchantable diameter (Dickens & Will, 2004). Many studies have evaluated the economics or GHG emission performance of bioenergy production in the USA (see e.g.: Cardoso, Özdemir, and Eltrop (2012); Hoefnagels, Junginger, and Faaij (2014); Pirraglia, Gonzalez, and Saloni (2012); Trømborg et al. (2013). Generally, the total bioenergy production costs (excluding distribution) are dominated by the total biomass delivery costs to factory gate (Humbird et al., 2011; Mobini, Sowlati, & Sokhansanj, 2013; Rentizelas, Tolis, & Tatsiopoulos, 2014).

As indicated above, the expected increase in wood harvest for bioenergy is likely to affect the carbon balance and economic performance of forestry plantations. The studies mentioned above only focus on either the economic performance or carbon balance of plantation management strategies, consider bioenergy as a solitary industry or neglect the displaced GHG emissions due to product substitution. A detailed and simultaneous quantification of the carbon balance and economic performance contribute to an informed decision making on embedding the increasing bioenergy demand in the current forestry sector. Such assessment for different plantation management strategies is important for the selection of the optimal plantation management strategy in terms of economics or carbon accumulation given the expansion of demand for bioenergy. Therefore, the goal of this study is to evaluate the carbon balance over time and economic performance of different loblolly pine plantation management strategies in the Southeastern USA for the production of wood pellets. To do this, the research defines the wood class yield at thinning or final harvest, cultivation, harvest, and transport costs, and the total carbon balance of three different plantation management strategies, each with and without slash utilization.

3.2 Materials and methods

3.2.1 General approach

The aim of this study is to quantify the impact of plantation management choices on the GHG and economic performance of bioenergy production using loblolly pine in the Southeastern USA. Therefore, the cumulative carbon balance and the net present value of a loblolly pine plantation is calculated (considering a 1 ha plot, or 10^4 m^2) as well as calculating the wood supply cost for bioenergy production for different management strategies. The plantation management strategies affect both the overall yield of the loblolly pine plantation as well as the composition of the yield in terms of different wood classes (sawtimber, chip-n-saw and pulpwood and slash). It is assumed that 80 % of the harvested pulpwood is utilized for pulp and paper production, and that the other 20 % is used for bioenergy production. Slash wood (logging residues) are the residues of the otherwise un-merchantable tops and branches of the harvested trees and is considered as optional bioenergy feedstock, similar to (Dwivedi, Khanna, Sharma, & Susaeta, 2016).

The following paragraphs describe the different steps to determine the total carbon balance and economic performance of different plantation management strategies. To illustrate the dynamics of the carbon accumulation over time the carbon balance is calculated for an individual stand.

3.2.2 Plantation management strategies

The loblolly pine plantation management strategies are named “conventional” (C), “additional thinning” (AT) and “short rotation” (SR). See Table 3-1 for the characteristics of each plantation management strategy. The *conventional* management strategy represents a currently applied management strategy that yields a mix of sawtimber, chip-n-saw and pulpwood, in a rotation of 25 years with a mid-rotation thinning at year 15, as described by Perlack and Stokes (2011). The *short rotation* management strategy defined here involves a rotation period of 16 years with high planting density to attain a high biomass accumulation. To enable a high yield level, the fertilizer application and application of agrochemicals is higher compared to the conventional strategy (Gonzalez et al., 2012; Lu et al., 2015). The *additional thinning* strategy has an increased amount of seedlings in combination with in total two thinnings at age 10 and age 15, to yield a high amount of pulpwood, with no or limited effect on the mix of sawtimber and chip-n-saw wood yield (Perlack & Stokes, 2011). For each management strategy a sub-strategy is included, which includes the collection and utilization of ‘slash’.

Table 3-1. Silvicultural plantation management practices of the three main plantation management strategies.

	Plantation management strategies (abbreviation)		
Management item	**Conventional[A] (C)**	**Short rotation (SR)[B]**	**Additional thinning[C] (AT)**
Site prep intensity	Medium	High	High
Planting density (ha^{-1})	1500	3000	3000
Year of herbicide application	1	1 & 3	1 & 3
Phosphorus fertilization rate as diammonium phosphate in kg ha^{-1}, expressed in kg phosphorus (year of application)	17.5 (4 & 8)	22 (4 & 6)	22 (4, 10 & 15)
Nitrogen fertilization as urea in kg ha^{-1}, expressed in kg nitrogen (year of application)	155 (4 & 8)	199 (4 & 6)	199 (4, 10 & 15)
Year of the thinning, expressed in years after plantation establishment (thinning intensity[D])	15 (30 %)	No	10 (50 %) 15 (30 %)
Year of final harvest, expressed in years after plantation establishment	25	16	25

[A] Presently, a common loblolly pine management strategy (Perlack & Stokes, 2011).
[B] A management strategy with high initial planting density, no thinning, and early clear-cut harvest, similar to (Lu et al., 2015).
[C] A management strategy to maximize volume growth by increased planting density and early thinning, as described by (Scott & Tiarks, 2008).
[D] The thinning intensity describes the percentage of (live) trees harvested during thinning.

3.2.3 Model framework

A model is constructed to calculate the total carbon balance and carry out the economic analysis of the different loblolly pine plantation management strategies. A visualisation of the data input, calculation steps and final results in this analysis are shown in Figure 3-1. The characteristics of the plantation management strategies define the growth parameters, which determine the diameter, height and volume growth curve. The individual tree volume and number of live trees determines the total wood volume per hectare at each year of the rotation period. The volume growth curve of loblolly pine trees and the harvested wood classes are key input to calculate the in-situ and ex-situ carbon pools of each plantation management strategy. The volume growth curve (all wood classes) determines the live tree carbon pool. The decaying wood carbon pools are based on the tree mortality and tree component distribution. The tree component distribution describes the mass distribution of total tree volume over fine-, coarse-, taproots, stem wood, stembark, branches and foliage. The harvested wood is categorised to four different wood product categories (long, medium-long, medium short and short life wood products), each with a specific processing efficiency, displacement factor, and wood product lifespan.

As the economic values of the harvested wood classes differ significantly, total plantation management costs of the different plantation management strategies are economically allocated to the different wood classes harvested. Adding the harvesting, collection and transport costs to the cultivation costs of loblolly pine results in the total delivery costs of pulpwood size wood or slash wood. In particular the harvesting costs may differ between different plantation management strategies due to the difference in harvesting equipment capacity, a result of the difference in tree diameter and tree volume at time of harvest.

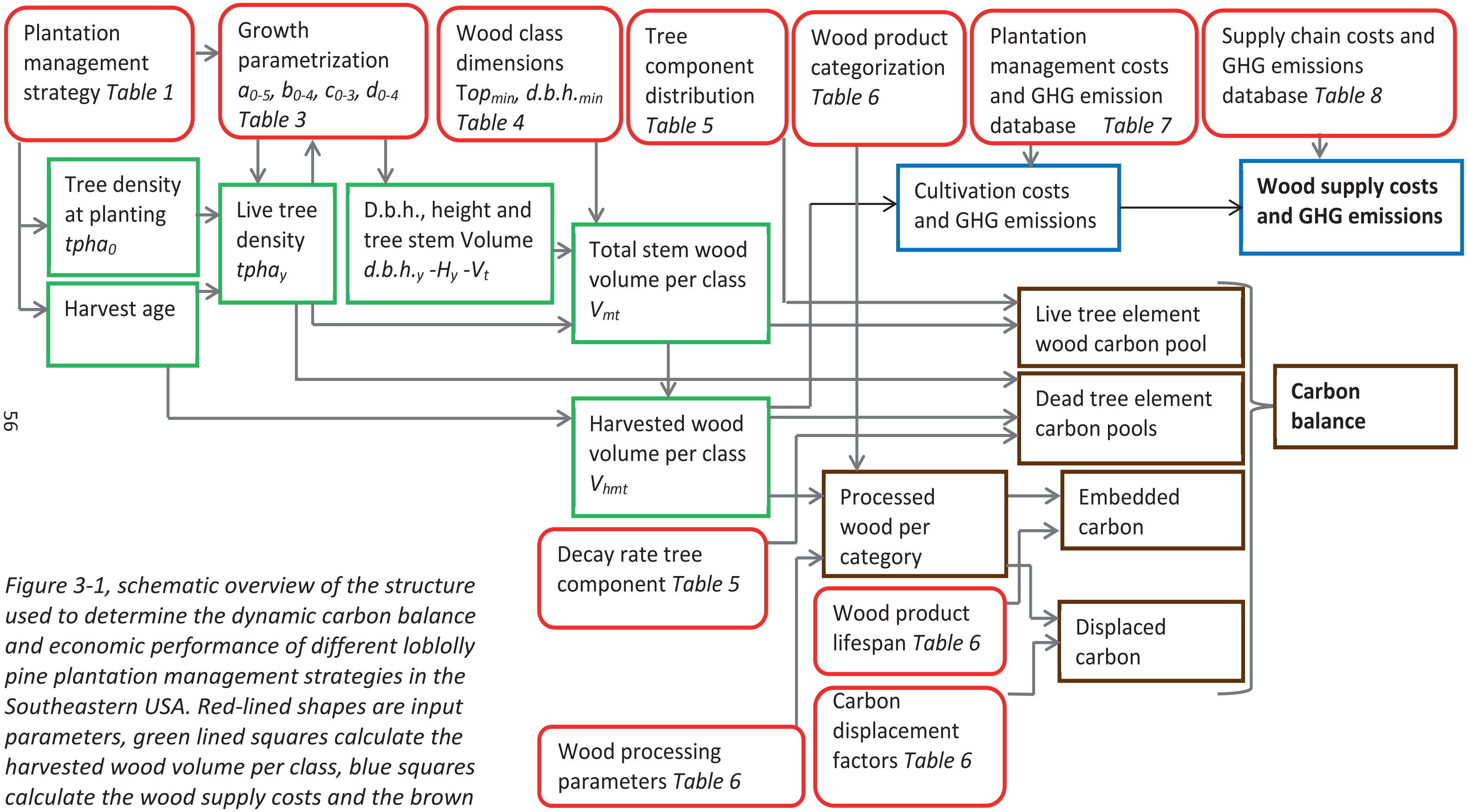

Figure 3-1, schematic overview of the structure used to determine the dynamic carbon balance and economic performance of different loblolly pine plantation management strategies in the Southeastern USA. Red-lined shapes are input parameters, green lined squares calculate the harvested wood volume per class, blue squares calculate the wood supply costs and the brown shapes calculate the total dynamic carbon balance.

3.2.4 Volume growth of loblolly pine trees

The modelling of total wood yield and classification into pulpwood, chip-n-saw and sawtimber-size wood is simplified to five growth equations. First, the tree survival rate is determined, this is based on the soil quality, initial tree density and age of the plantation, see Equation 1, derived from (Harrison & Borders, 1996). The diameter at breast height (d.b.h.) and total tree height are determined with Equation 2 and 3, assuming a typical S-shaped growth curve, similar to Scott and Tiarks (Scott & Tiarks, 2008). The diameter and height are used to determine the average individual tree volume (to merchantable top diameter), similar to (Harrison & Borders, 1996), see Equation 4. Combining the tree volume (Equation 4) and tree survival (Equation 1) the total wood volume per hectare in each rotation age can be determined. Finally, the total wood volume is classified into sawtimber, chip-n-saw, pulpwood, and slash-size wood using the individual wood class dimensions for d.b.h. and top diameter (top_{minwc}), see Equation 5, similar to (Susaeta, Lal, Alavalapati, Mercer, & Carter, 2012b). To determine the quadratic diameter ($d.b.h._q$) and the diameter of pulpwood size trees, a normal distribution of tree diameter is considered, based on the diameter distribution shown in (Albaugh et al., 2004).

$$tpha_t = a_0 + \left[(tpha_i - a_0)^{-a_1} + {a_2}^2\, a_3 ({t_t}^{a_4} - {t_i}^{a_4})\right]^{-\frac{1}{a_1}}$$ **Equation 1**

$$d.b.h._t = b_0\left[1 - e^{-b_1 b_2 t}\left[1 - (b_3)^{-b_1}\right]\right]^{-\frac{1}{b_1}}$$ **Equation 2**

$$H_t = c_0\left[1 - e^{-c_1 c_2 t}\left[1 - (c_3)^{-c_1}\right]\right]^{-\frac{1}{c_1}}$$ **Equation 3**

$$V_t = d_0 d.b.h._t.^{d_1}\, d_2 {H_t}^{d_3}$$ **Equation 4**

$$V_{mwct} = tpha_t V_t^{\left[-e_0\left(\frac{top_{\min wc}}{d.b.c._q}\right)^{e_1} - e_2 \frac{tpha_t}{2.47}^{-e_3\left(\frac{d.b.h._{\min wc}}{d.b.h_q}\right)^{e_4}}\right]}$$ **Equation 5**

Variable	**Description**	**Unit**
$tpha_t$	Trees per hectare at age t of plantation	trees ha^{-1}
$a_0 - a_4$	Tree survival parameters (regression analysis)	[-]
$tpha_i$	Trees per hectare at planting or given age i	trees ha^{-1}
i	Initial age (0) or given age i	years
t	Age of plantation	years
$d.b.h._{(t)}$	Diameter at age *t*	cm
$b_0 - b_3$	D.b.h. growth parameters (regression analysis)	[-]
$H_{(t)}$	Height at age *t*	m
$c_0 - c_3$	Height growth parameters (regression analysis)	[-]
$V_{(t)}$	Stem volume at age t	Mg $tree^{-1}$
$d_0 - d_3$	Volume growth parameters (regression analysis)	[-]
V_{mwct}	Merchantable volume of specific wood class (wc) in at	Mg ha^{-1}

	age t	
$e_0 - e_4$	Volume classification parameters (regression analysis)	[-]
top_{min}	Minimal top diameter wood class (wc)	cm
$d.b.c._q$	Quadratic diameter based on diameter breast height	cm
$d.h.b._{min}$	Minimal diameter breast height of a wood class (wc)	cm

3.2.5 Carbon balance

The total carbon balance dynamics of managed forests includes five main carbon pools that change over time: wood supply chain GHG emissions, live tree carbon, dead tree carbon, embedded biogenic carbon in final wood products, and avoided fossil GHG emissions by product substitution. Wood supply chain GHG emissions include all fossil GHG emission associated with plantation management, harvesting and transport. Based on the tree stem volume growth (see section 3.2.4) and the tree component distribution, the total carbon sequestered by live trees is determined for both below- as well as aboveground tree elements. The dead carbon pools include dying trees (based on Equation 1) and the residual tree components left in the plantation after thinning or final harvest. For each tree component a specific decay rate is taken into account as small debris decays faster compared to thicker debris. The decay rate is defined as the percentage of decaying wood loss per year (C.a. Gonzalez-Benecke et al., 2015). To account for the embedded carbon in wood products, each harvest is categorised into four product categories, each category with a specific wood processing efficiency and product lifespan. As the use of wood products substitutes the use of alternative products (steel, concrete, etc.) a carbon displacement is considered. The carbon displacement expresses the carbon efficiency of wood product use over the use of other materials and quantifies the amount of GHG emissions avoided, similar to the definition of (Sathre & Connor, 2010). The total dynamic carbon balance is determined for several plantation management cycles, and expressed as Mg carbon per hectare (Mg ha^{-1}). Based on this dynamic trend, a linear trend line is plotted, this enables a more fair comparison at every given time, despite the differences in rotation length.

3.2.6 Total wood supply costs of loblolly pine wood

Cultivation costs of loblolly pine

The cultivation costs are determined using Equation 6, which include the allocation of plantation management costs. According to the wood class prices, the factor *f* represents the economic allocation factor of each wood class. As these wood class prices vary over time, for this analysis a 5-year average is considered.

$$\text{Biomass cultivation cost}_{\text{wc}} = \frac{\sum_{t=1}^{t=ht} \frac{\sum_{n=1}^{N}\left(O_{ny} \times C_{ny} \times f_{wc}\right)}{(1+a)^{y}}}{\sum_{t=1}^{t=ht} \frac{V_{mwct}}{(1+a)^{t}}}$$

Equation 6

Item	**Description**	**Unit**
Biomass cultivation costs$_{wc}$	Discounted cultivation costs of wood class	\$ Mg^{-1}
O$_{nt}$	Occurrence cost item per ha$_{n}$ in year t	#
C$_{nt}$	Costs of item n in year t	\$ ha^{-1}
F$_{wc}$	Economic allocation factor of wood class	[-]
V$_{mwct}$	Merchantable volume in year t	Mg ha^{-1}
a	Discount rate	%
t	Age of the rotation	Year
ht	Year of final harvest	Year

Harvesting and transport of pulpwood and biomass

The harvesting costs include all costs associated with the felling, skidding and loading of loblolly pine trees at thinning age or at final harvest. Costs for harvest operations are simplified to divide hourly operational costs by hourly capacity of the machines. Hourly costs are commonly determined by considering the investment costs, lifetime, utilization rate, fuel consumption, lube and oil costs and labour wages (Brinker, Kinard, Rummer, & Lanford, 2002) (Akay, 1998; Turhollow & Sokhansanj, 2009). Only for felling is the hourly productivity linked to tree diameter, as felling small diameter trees reduces productivity significantly (Li, Wang, & Mcneel, 2006). Equation 7 determines the felling costs for loblolly pine trees. To determine the total transportation costs, both fixed and variable transport costs are considered.

$$\text{Felling costs} = \frac{\text{Hourly cost} \times (\text{a} \times \text{d.b.h.})}{V_{\text{mwct}}}$$

Equation 7

Item	**Description**	**Unit**
Felling costs	Biomass felling costs	\$ Mg^{-1}
Hourly cost	Hourly operational costs of harvesting machinery	\$ h^{-1}
a	Felling time per diameter of the tree stem	h cm^{-1}
d.b.h.	Diameter breast height	cm
V$_{mwct}$	Tree volume at harvesting age t	Mg tree^{-1}

3.2.7 CO_2 abatement costs

Carbon dioxide abatement costs are calculated for the plantation management strategies using the difference in both the total carbon balance and the plantation management costs compared to the conventional strategy. This approach is adapted from the carbon dioxide abatement costs approach found in (Dwivedi et al., 2015). The carbon abatement costs are expressed in \$ per Mg CO_2 (\$ Mg^{-1}) using Equation 8.

$$\mathrm{CO_2\ abatement\ costs} = \frac{\sum_{y=1}^{y=100} \frac{\sum_{n=1}^{N}(V_{mwct} \times (BCC_n - BCC_c)}{(1+a)^y}}{(C_n - C_c)} \times \frac{44}{12}$$

Equation 8

Item	**Description**	**Unit**
CO_2 abatement costs	Costs for CO_2 abatement expressed per Mg carbon dioxide	\$ Mg^{-1}
V_{mwct}	Merchantable volume of specific wood class (wc) in at age t	Mg ha^{-1}
BCC_n	Biomass cultivation costs of strategy *n*	\$ Mg^{-1}
BCC_c	Biomass cultivation costs of the conventional strategy	\$ Mg^{-1}
a	Discount rate	%
t	Year of the rotation period	Year
C_n	Linear carbon balance after 100 year of strategy *n*	Mg ha^{-1}
C_c	Linear carbon balance after 100 year of the conventional strategy	Mg ha^{-1}
44/12	CO_2 to C mass ratio	-

3.2.9 Sensitivity analysis

A sensitivity analysis provides insight on the results by varying the key input parameters used in this analysis to determine total carbon balance and cultivation costs. To vary in the sensitivity analysis in this analysis the diameter growth curve, volume growth curve, displacement factors, difference between displacement factors, price of wood classes and the difference in price between wood classes are expected to affect the result to a large extent. The diameter growth and individual tree growth curve are key intermediate results, as shown in Figure 3-1. The diameter growth also impacts the wood classification and affects the total volume growth, and thereby, indirectly affects the carbon balance and economic performance. The variation in tree volume impact the harvested wood volume, while the wood classification remains unchanged, to show the impact on increased yield without variation in wood classification (und subsequent no change in carbon displacement factors for these classes). The potential impact of soil quality, availability of water, nutrient availability and other factors are lumped in the tree diameter growth variation. Tree diameter change impact the tree volume and the classification of harvested wood.

The price of sawtimber, chip-n-saw and pulpwood have a clear impact on the allocation of plantation management costs to the different wood classes and thereby influence the economic performance. The displacement factors are important for the carbon balance over time, especially over longer time frames.

Table 3-2, Sensitivity analysis parameter, range of variation and affected result.

	Parameter variation %	Cultivation costs	Carbon timeline
Diameter growth parameter b_0	+/- 20[A]	X	X
Tree volume	+/- 35[B]	X	X
Price difference between pulpwood and sawtimber	+/- 20[C]	X	
Displacement factor variation	+/- 50[D]		X
Variation in the difference between displacement factors used for the different wood categories	+/- 50[D]		X

[A] By changing the management intensity (with similar planting density and site quality) a d.b.h. difference up to 20 % is reported by (Zhao, Kane, & Borders, 2011). Therefore, a 20 % variation in parameter b_0 is taken into account.

[B] Total wood volume difference between operational and intensive management reduces with age (when not thinned) (Zhao et al., 2011). As the youngest harvest age is 10 year, the associated difference is considered at this age, 32 % (Zhao et al., 2011), as basis for the tree volume variation taken into account in this sensitivity analysis.

[C] In recent decade timber prices for pulpwood, chip-n-saw and sawtimber usually follow a similar trend (TimberMart South), the variation in the difference between pulpwood and sawtimber prices is limited. The observed variation in the price difference over the time period 2011-2016 is approximately 15 %, in this analysis a variation of 20 % is taken into account.

[D] As shown by the meta-analysis of Sathre and O'Connor (2010) a large variation in carbon displacement factors is found in the literature; between -2.3 and 15 Mg Mg^{-1} (depended on wood product type and studied supply chain). This variation includes unlikely product substitutions, the most common displacement factors are in the range of 1.0 to 3.0 Mg Mg^{-1} (Sathre & O'Connor, 2010). To account for the potential variation in displacement factors, a variation of 50 % is taken into account.

3.3 Data input

3.3.1 Growth parameters and wood allocation

At each year of the plantation rotation cycle, the growth and wood yield Equations 1-5 are used to determine the total wood volume per harvested wood class. Details of the growth input parameters used in Equation 1-5 are presented in Table 3-3.

Table 3-3, Growth parameterization for loblolly pine growth determined with Eq. 1-5.

	Trees per hectare (t.p.h.a.$_t$)	Diameter breast height (d.b.h.$_y$)	Height (H_t)	Tree volume (V_t)	Wood class volume of the tree (V_{mt})
	a[A]	b	c[B]	d[C]	e[d]
0	247	-2.77 x LN(t.p.ha.)+α[E]	25	0.1823	-1.0344
1	-0.74534	0.037[F]	0.013	1.826	3.9498
2	0.0003425	α+β x t.p.h.a.$_t$[G]	11	0.006214	-5.0629
3	50	8 or 10[H]	0.06	1.22196	-0.37045
4	1.9747	-	-	-	6.0046

[A] To model the tree survival rate, a survival prediction equation is considered, for which the parametrization is taken from, using a lower asymptotic survival of 494 trees hectare^{-1} (value a_0) (Harrison & Borders, 1996).

[B] The impact of planting density on the height growth curve is limited (Pienaar, Shiver, & Harrison, n.d.). Therefore, no relationship between tree density and height for the different management strategies is considered in this analysis.

[C] The stem volume parameters are directly taken from Harrison and Borders (1996), and are specific for loblolly pine growth (inside bark) in the Lower Coastal Plain of the Southeastern USA.

[D] The parameters used in Equation 5 are obtained from (Susaeta et al., 2012b), based on work of (Amateis, Burkhart, & Burk, 1986).

[E] A natural logarithmic relationship between the planting density and the growth parameter a_0 used, based on the data provided in the planting density study of Pienaar, Shiver, and Harrison (n.d.).

[F] Since a relationship between diameter growth parameter b_1 and planting density on diameter growth is not evident, a universal value of 0.037 is considered, which matches the growth increase of the diameter found in (Pienaar et al., n.d.).

[G] A linear relationship between planting density and growth parameter b_2 is used to model the diameter growth, similar to the growth curve found in (Pienaar et al., n.d.). Values of -0.00002 and 0.0656 are considered for α and β respectively, derived from (Pienaar et al.,, (n.d.).

[H] To match the growth curve specified in (Pienaar et al., n.d.) for different planting densities a value of 8 is considered for tree survival parameter $a_{3,}$ however, to consider the influence of vegetation control on wood yield a value of 11 is considered for the short rotation management strategy.

To determine the merchantable volume of sawtimber, chip-n-saw and pulpwood size wood, the dimensions used in Equation 5 are presented in Table 3-4. In this analysis, only the minimal diameter at breast height (d.b.h.$_{min}$) and the minimal top diameter (top_{min}) are considered. Table 3-4 also presents the economic value of the different wood classes, this enables the economic allocation of softwood plantation management costs to the individual harvested wood classes.

Table 3-4, Softwood classifications for harvested wood classes used in this study

Classification[A]	Diameter breast height range [cm]	Minimal top diameter [cm]	Average price [\$ Mg^{-1}][C]
Slash	7.5 – 11	2.5	11
Pulpwood size	11 – 19	11.4	24
Chip-and-saw size	19 – 29	15.2	42
Sawtimber	> 29	17.8	64

[A] In this analysis the wood class ‘slash’ is included for the sub management strategies.

[B] Average price is based on the timber price of the last five year, as presented by (Timberupdate, n.d.), and converted to \$ Mg^{-1}.

3.3.2 Carbon balance, in-situ and ex-situ

The mass distribution and decay rates to determine the carbon of the different live or dead tree components, are shown in Table 3-5. Both the above- and belowground tree mass is further distinguished into smaller tree components, all with a specific decay rate when left in the field after harvest or death. To determine the ex-situ carbon pools (embedded and displaced carbon) the wood processing efficiency, lifespan of wood products and displacement factors are specified in Table 3-6. Both slash and pulpwood are considered as potential feedstock for wood pellet production, aimed as fuel for power plants in Northwestern Europe. The displacement factors are directly taken from literature and expressed as the Mg of fossil carbon displaced by one Mg (Mg Mg^{-1}) of carbon embedded in wood products. The displacement factors include the processing of wood into wood products and the reference products. However, these carbon displacement factors do not include the landfilling of wood products after use. Sathre and Connor (2010) found only small differences in studies reporting the displacement factors of wood products that are landfilled.

Table 3-5, Mass distribution and decay rates of loblolly pine tree components.

	Component	Mass percentage of total live trees [%]	Decay rate (%)[c]
Below ground biomass (22 %)[A]	Fine roots	1.8[B]	15
	Coarse roots	4.4[B]	12
	Tap roots	15.8[B]	10
Above ground biomass (78 %)[A]	Stemwood	60.1[D]	10
	(Stem)bark	6.4[DE]	10
	Branches	7.3[D]	12
	Foliage	3.8[D]	15

[A] According to Samuelson et al. (2004), below ground biomass represents approximately 22-25 % of total tree mass in young pine stands.

[B] The total belowground biomass is distributed over tap roots (75 %), coarse roots (18 %) and fine roots (8 %) based on (Samuelson et al., 2004).

[C] Reported decay rates for foliage, coarse woody debris, and lateral roots are 15, 12 and 10 % mass loss per year, respectively (C.a. Gonzalez-Benecke et al., 2015). These values are utilized for thick stemwood and tap roots, branches and coarse roots or foliage and fine roots.

[D] Above ground tree component distribution are based on values reported by Subedi (2008, 2012).

[E] (Stem) bark is approximately 8.5 % of total aboveground biomass (Jokela & Martin, 2000).

Table 3-6. Wood processing efficiency, distribution of harvested wood classes to wood product categories and carbon displacement factors for the different wood classes.

		Wood class			
		Sawtimber	Chip-n-saw	Pulpwood	Slash
Wood conversion efficiency (%)		65 %[A]	65 %[A]	58 %[A]	78 %[C]
Wood product category (lifespan)	Long (50 years)	50[A]	25[A]	0[A]	0
	Medium-long (16)	25[A]	25[A]	0[A]	0
	Medium-short (4)	0[A]	0[A]	33[A]	0
	Short (1)	25[A]	50[A]	67[A]	100[B]
Carbon displacement factor (Mg Mg^{-1})[D]		2.1	1.8	1.5	0.5[E]

[A] The proportion of wood class to harvested wood product categories and the conversion efficiencies are based on wood product characteristics as specified by Gonzalez-Benecke et al. (2015).

[B] In this analysis, it is assumed that the collected slash is fully utilized for bioenergy production, and therefore classified as short lifespan wood product category.

[C] The mass conversion of harvested carbon to wood pellets is 1.56 Mg Mg^{-1} harvested (Jan Gerrit Geurt Jonker et al., 2014), yields a carbon conversion efficiency of 78 % (assuming a carbon content of 50 %).

[D] The range of carbon displacement factors for common wood products is between 1.0 and 3.0 Mg Mg^{-1}, with a wood product average of 2.1 Mg Mg^{-1} (Sathre & Connor, 2010; Sathre & O'Connor, 2010). Sawtimber can be used for a variety of timber products, whereas pulpwood can only be used for a small selection of wood products. Therefore, the displacement factors are varied in this analysis, similar to the study of Pingoud, Pohjola, and Valsta (2010).

[E] For the utilization of slash for bioenergy (wood pellets for electricity) this analysis considers an average fossil fuel GHG comparator of electricity (198 g MJ^{-1} (EC European Commission, 2010)) to determine the carbon displacement factor.

3.3.3 Plantation management costs and GHG emission

Costs and GHG emissions of loblolly pine plantation establishment and maintenance are collected from various publications. Table 3-7 presents an overview of silvicultural practices and their associated costs and GHG emissions, along with the background information. A detailed overview of the plantation management practices per strategy is shown in the supplementary information, Table 3-S.1.

Table 3-7, Costs and GHG emissions of Loblolly pine plantation management practices.

Function	**Main equipment**	**\$/quantity**	**CO_2eq./quantity**
Site preparation	Shear, rake and pile	175 \$ha^{-1} [A]	167 kg ha^{-1} [b]
	Bedding	370 \$ ha^{-1} [C]	202 kg ha^{-1} [D]
Planting	Mech. planting	310 \$ ha^{-1} [E]	109 kg ha^{-1} [F]
Aerial application agrochemicals	Helicopter	31 \$ ha^{-1} [G]	28 kg ha^{-1} [H]
Herbaceous weed control	Backpack	45 \$ ha^{-1} [I]	62 kg ha^{-1} [J]
Seedlings		0.075 \$ seedling^{-1} [K]	0.027 kg seedling^{-1} [L]
Fertilizers	DAP	464 \$ Mg^{-1} [M]	2.03 kg kg^{-1} [N]
	Urea	273 \$ Mg^{-1} [O]	5.15 kg kg^{-1} [N]
Herbicide	Velpar ULW	70 \$ ha^{-1} [P]	62 kg ha^{-1} [J]

[A] Total site preparation (including bedding) is 492 \$ ha^{-1} (Susaeta et al., 2012b), to calculate the shear, rake and piling costs, the costs for bedding is subtracted from the total site preparation costs.

[B] Using a diesel consumption of 43 L ha^{-1} for site preparation (Markewitz, 2006) and a GHG emission intensity of 3.89 kg L^{-1} of diesel is based on total carbon emission intensity of diesel is 24.1 g MJ^{-1} (Macedo et al., 2008) and Higher Heating Value of diesel of 44 MJ L^{-1}, (Hamelinck, Hooijdonk, & Faaij, 2005).

[C] Bedding costs were 324\$ ha^{-1} in the Southern Coastal Plain in 2012, (Eric Dooley & Barlow, 2013).

[D] A diesel consumption of 52 L ha^{-1} is considered for tractor with bedding plow, based on (Markewitz, 2006), combined with the GHG emission intensity of diesel as specified under footnote B.

[E] Although hand planting may be less expensive, in this analysis the use of mechanized planting is considered at a costs of 344$ ha^{-1}, typical for the Southeastern USA (Eric Dooley & Barlow, 2013).

[F] Diesel consumption of a skidder with tree planter is 28 L ha^{-1} (Markewitz, 2006),

[G] The hourly operational costs of a helicopter are specified as 1200 $ h^{-1} (USDA Forest Service, 2012) and the time occupation is estimated as 0.023 h ha^{-1} (Markewitz, 2006), in line with cruising speed and the width of a spray boom of a helicopter.

[H] Helicopter fuel use is 9 L ha^{-1}, based on (Markewitz, 2006), and a GHG emissions intensity of 3.081 kg L^{-1}. The GHG emission intensity of jet fuel is based on the direct combustion emissions of 2.529 kg L^{-1} (Elgowainy et al., 2012) and supply chain GHG emissions of 15 gram MJ^{-1} (DG Ener, 2015), heating value of 46.2 MJ kg^{-1} and density of 0.802 kg/l, based on (Elgowainy et al., 2012).

[I] Chemical treatment to control herbaceous weeds with herbicides using a backpack is 38 $ ha^{-1} (Eric Dooley & Barlow, 2013).

[J] The application of herbicides has a total GHG emission intensity of 62 kg ha^{-1} (including production of herbicides), similar to (Dwivedi et al., 2012).

[K] The costs for seedlings may range between 0.057 and 0.420 $ seelings^{-1} (Aborgen, 2016), in this analysis costs per seedling are assumed to be 0.075 $ seedling^{-1}, similar to (Sunday et al., 2014).

[L] GHG emissions associated with the seed orchard, nursery and transport to the plantation (total of 40.92 kg CO_2 for 1500 seedlings (Chapagain, 2012)) is recalculated to 0.027 kg seedling^{-1} delivered to a loblolly pine plantation.

[M] Price of urea considered for August 2015, based on (“Indexmundi,” 2016a) urea contains approximately 44 – 46 % nitrogen

[N] Data retrieved from (Brentrup & Palliere, 2008), GHG emissions include production but also application phase.

[O] Price of DAP considered for August 2015, based on (“Indexmundi,” 2016b) DAP contains approximately 22 % phosphorus

[P] Herbicide application, excluding equipment for distribution, based on (Susaeta et al., 2012b).

3.3.4 Wood delivery costs

Table 3-8 lists the costs and GHG emissions of harvest operations for softwood harvesting. The harvesting system includes a feller-buncher, grapple skidder, pre-processor and loading station. Despite higher felling costs for a feller-buncher compared to chainsaws, the total harvesting system productivity and costs for the whole system including feller bunching and a grapple skidder are lowest (Li et al., 2006).

Table 3-8, Costs and GHG emissions of Loblolly pine harvesting equipment .

Function	**Main equipment**	**Capacity**	**Costs of harvest and transport activities**	**GHG emission intensity**
Felling	Feller buncher	Variable[A]	130 $ h^{-1} [B]	88 kg h^{-1} [C]
Skidding	Grapple skidder	30 Mg h^{-1} [D]	105 $ h^{-1} [E]	118 kg h^{-1} [F]
Loader	Loading station	60 Mg h^{-1} [G]	125 $ h^{-1} [H]	118 kg h^{-1} [F]
Transport	Truck with trailer	-	11.7 $ Mg^{-1} [I]	12.5 kg Mg^{-1} [J]
Slash collection	Slash collection with skidder	30 Mg h^{-1} [D]	16 $ Mg^{-1} [K]	3.93 kg Mg^{-1} [L]

[A] The capacity of a feller buncher is strongly related to the tree diameter for a diameter range between 12 – 37 cm (Li et al., 2006).

[B] Based on the high capacity feller buncher, as described in (Lu et al., 2015).

[C] Assuming diesel consumption of 22.7 L h^{-1} (Markewitz, 2006) and a GHG emission intensity of 3.89 kg L^{-1} of diesel production and consumption, footnote B of Table 3-5.

[D] Skidder capacity may vary according to tree volume, skidding distance and slope of the terrain. In this analysis a skidder productivity of 30 Mg ha^{-1} is considered, based on (Lu et al., 2015).

[E] Based on the high capacity skidder, as described in (Lu et al., 2015).

[F] A diesel consumption of 30.3 L h^{-1} is considered for the skidder as well as the loader,

[G] assuming a high loader, as described in (Lu et al., 2015).

[H] Capacity of a tree loader, based on (Lu et al., 2015; Mobini et al., 2013)

[I] Based on the updated fixed and variable truck transportation costs of 4.32 $ Mg^{-1} and 0.134 $ Mg^{-1} km^{-1} respectively (Lu et al., 2015).

[J] Using a diesel consumption of 0.69 L km^{-1} (Cardoso et al., 2012; J.G.G. Jonker et al., 2016), GHG emission intensity diesel and empty returns using 40 % of diesel compared to loaded trip (Hamelinck et al., 2003).

[K] Collection of slash residues and delivery to in-forest landing place, based on (Rummer, Len, & O'Brien, 2004).

[L] Using the fuel consumption of a skidder, 30.3 L h^{-1}, (Dwivedi et al., 2012), and the averaged capacity of 30 Mg h^{-1}, based on (Lu et al., 2015).

3.4 Results and discussion

3.4.1 Wood yield

The calculated wood yield per wood class for the different loblolly pine plantation management strategies in the Southeastern USA are shown in Figure 3-2. The wood yield is expressed in dry Mg wood ha^{-1} yr^{-1}. In general, increasing plantation management intensity and planting density increases annual wood yield, especially for the short rotation management strategy. However, this management strategy yields very little sawtimber wood class and low amount of chip-n-saw size wood. This is a result of the reduced diameter growth at larger planting densities and early harvest age. The conventional and additional thinning strategy yield similar amount of sawtimber and chip-n-saw size wood, however, due to the increased planting density at planting the first and second thinning yield almost exclusively pulpwood-size wood or slash. The slash yield is higher for the additional thinning and short rotation management strategy due to the early thinning or harvest, as younger trees yield relatively higher amounts of slash. Currently, slash is not used for wood pellet production, mainly due to the low quality of the feedstock. Slash could however be used as boiler fuel in e.g. saw mills, substituting more high-quality residues such as sawdust and shavings, which in turn could be used for wood pellet production.

The growth equations used to calculate the average tree growth is based on five growth equations, using this simplified approach may result in an under- or overestimation of the growth of the total stand. Furthermore, there is a risk that harvested wood is classified wrongly. A comparison of wood class yield with another study shows similar results for the distribution of pulpwood, chip-n-saw and sawtimber wood (Dwivedi & Khanna, 2015). The key variable in the growth simulation is the diameter growth, as it is the key parameter for tree volume and product volume classification. Although the diameter growth parametrization is based on a somewhat older study (Pienaar et al., n.d.), a more recent analysis of (Zhao et al., 2011) showed a similar diameter growth curve as simulated in the current analysis. However, the parametrization of the growth equations used for this study were based on empirical data for lower planting densities. For higher planting densities, more empirical data to enable better parametrization would be preferred.

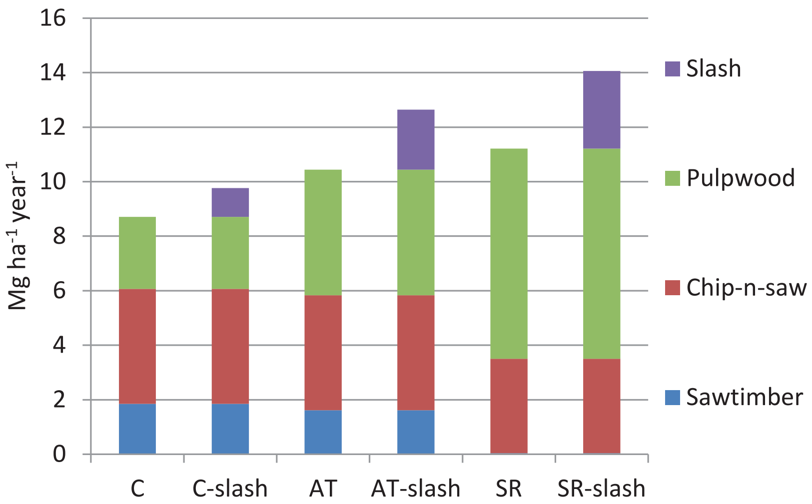

Figure 3-2. Wood class yield for the conventional (C), additional thinning (AT) and short rotation (SR) loblolly pine management strategies, expressed in Mg wood per hectare per year.

3.4.2 Carbon timeline of different plantation management strategies

Figure 3-3 visualizes the four in-situ and ex-situ carbon pools for the conventional management strategy to illustrate the build-up of the total carbon balance over several rotations. The live biomass carbon pool shows a typical growth curve, interrupted by a thinning and final harvest. The thinning and harvest are followed by an increase of the dead carbon pool, which slowly decays over time. Over the rotation cycle the dead carbon pool increases due to tree mortality. After the lifespan of the longest product life, equal amounts of carbon in harvested wood products are added and removed from the embedded biogenic carbon pool, resulting in a stable carbon pool. The displaced carbon, however, increases with each harvest, as with each harvest fossil GHG emissions are avoided due to product substitution.

In Figure 3-4, the total dynamic carbon balance and the linear carbon trend lines of the different plantation management strategies are shown. The increasing trend of the total carbon balance is due to cumulative fossil carbon displacement, while the oscillating curve is due to the tree growth cycles. The difference in harvest age between the conventional and short rotation strategy is clearly shown in Figure 3-4. During the 100-year simulation period the plantations are harvested each 16 or 25 years for the short rotation or conventional and additional thinning strategies. The total carbon stock after 100 years are 205 (247), 214 (268) and 149 (195) Mg ha^{-1} for the conventional, additional thinning and short rotation management strategies (in the parentheses is the same strategies with slash). However, when considering the average linear carbon trend line the carbon stock is 213 (244), 216 (259) and 194 (242) Mg ha^{-1} for the conventional, additional thinning and short rotation loblolly pine plantation management strategies respectively. Interestingly, the short rotation strategy with slash utilization accumulates high amounts of carbon in the beginning, but is surpassed by the additional thinning strategy with slash after 30 years. Without the utilization of slash, the short rotation management strategy accumulates the highest amounts of carbon early. After year 55 the additional thinning management strategy yields the most accumulated carbon per hectare, see Figure 3-4. Important to note is the influence of the composition of wood yield on the total carbon balance. For example, the wood yield of the short rotation management strategy is higher, however, it yields mainly pulpwood size material, which has a lower displacement factor (see Table 3-6). Similar is the difference between the conventional and the additional thinning strategy; the additional thinning strategy produces more wood, but the amount of sawtimber and chip-n-saw wood is equally resulting in a higher displacement of fossil carbon.

Especially for simulation periods of 100 years and longer, the carbon balance is dictated by the carbon displacement due to product substitution, in contrast to the stabilizing biogenic carbon embedded in wood products. The study of (Perez-Garcia, Lippke, Comnick, & Manriquez, 2006) also illustrated the high share of displaced carbon in the overall carbon balance, especially over longer time periods. The displacement factors included in this study are taken from the extensive review of displacement factors by Sathre and Connor (2010). The main issue with the use of generic carbon displacement factors is the lack of data regarding wood processing, utilization of wood products, product lifespan and end-of-life disposal of wood products (Brunet-Navarro, Jochheim, & Muys, 2016). Due to this lack of data the carbon displacement factors used in this study are uncertain. For bioenergy the carbon displacement factor is based on the average EU electricity mix, when considering a displacement factor based on coal powered electricity the carbon accumulation can be higher, especially for the short rotation strategy. Studies excluding the displacement of fossil carbon concluded that (for longer time frames) live trees are the largest carbon pool with only a limited share of embedded (biogenic) carbon, especially when producing short lifespan wood products (C.a. Gonzalez-Benecke et al., 2015; Carlos a. Gonzalez-Benecke et al., 2010). Excluding the displaced fossil carbon in the total carbon balance favours longer rotation periods for the production of sawtimber, as generally assumed this wood class is processed to longer lifespan wood products. However, including the carbon displacement factors shows the impact of different wood class yields outside the forest plantation. Therefore, it provides a better picture of the impact of plantation management decisions on the overall carbon balance. Finally, it is also debatable whether the carbon displacement factors should be kept constant over a 100 year time period. In Table 3-9 an overview of the dynamic and linear carbon balance of the different loblolly pine plantation management strategies is presented over the different time periods.

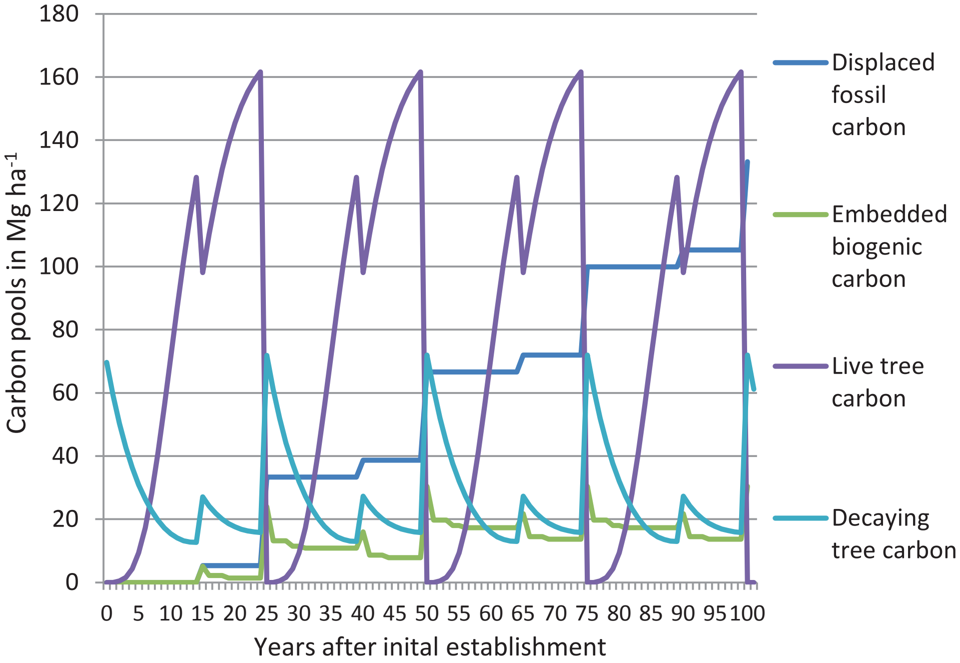

Figure 3-3 Dynamics in in-situ and ex-situ carbon pools of a loblolly pine plantation given a conventional management strategy.

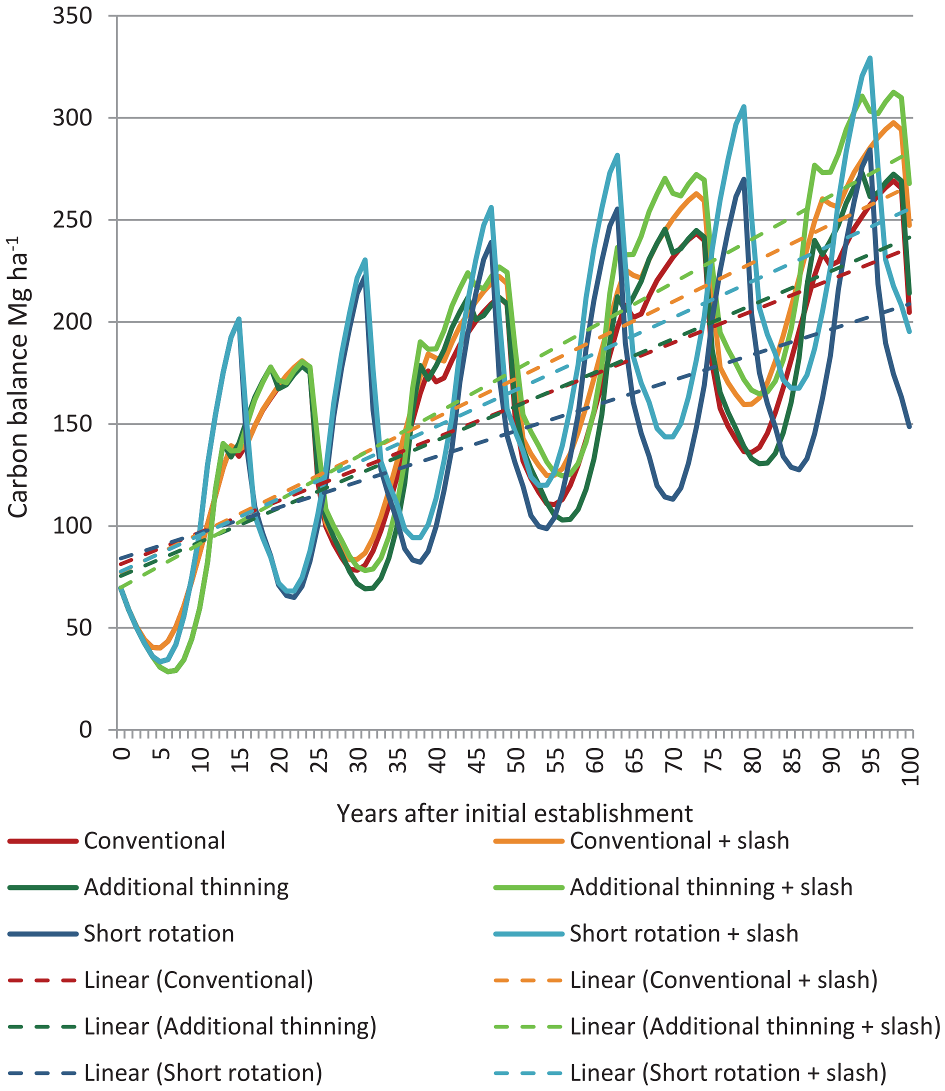

Figure 3-4, Total carbon balances of the conventional, additional thinning and short rotation plantation management strategies, with and without the utilization of slash, including linear trend line.

Table 3-9 Wood yield, cultivation costs and GHG emissions of pulpwood and slash production for different plantation management strategies in the Southeastern USA.

		Unit	**Conventional**	**Conventional slash**	**Additional thinning**	**Additional thinning slash**	**Short rotation**	**Short rotation slash**
C-balance	Year of the rotation age	$Mg\ ha^{-1}$	176	178	175	178	201	201
	Year after rotation age	$Mg\ ha^{-1}$	121	137	125	141	138	150
	Dynamically after 100 years	$Mg\ ha^{-1}$	205	247	214	268	149	195
	Dynamically after 200 years	$Mg\ ha^{-1}$	307	387	324	429	247	353
	Linear trend line after 100 year	$Mg\ ha^{-1}$	213	244	216	259	194	242
Costs	Allocated pulpwood cultivation costs	$\$\ Mg^{-1}$	17.92	17.32	17.86	16.60	21.49	19.57
	Allocated slash cultivation costs	$\$\ Mg^{-1}$	-	8.66	-	8.03	-	9.78
	Total pulpwood supply costs	$\$\ Mg^{-1}$	47	46	50	49	54	52
	Total slash supply costs	$\$\ Mg^{-1}$	-	42	-	41	-	43
GHG emissions	Allocated GHG emissions pulpwood	$kg\ Mg^{-1}$	3.81	3.69	3.99	3.71	7.21	6.56
	Allocated GHG emissions slash	$kg\ Mg^{-1}$	-	1.84	-	1.79	-	3.28
	Total (fossil) GHG emission of wood supply	$kg\ Mg^{-1}$	27.22	27.23	29.43	29.17	33.38	32.73
NPV	Plantation NPV	$\$\ ha^{-1}$	686	748	777	997	65	264
	CO_2 abatement costs	$\$\ Mg^{-1}$	-	-8	-7	-13	-	21

3.4.3 Economic performance of loblolly pine management strategies.

Consistent with expectations, increased plantation management intensity is associated with higher total plantation management costs, a result from increased seedling density, fertilizer use and herbicide application. For all management strategies, the land costs are the largest share of the total plantation management costs, see Figure 3-5 (see supplementary information for more detail). Figure 3-5 shows the total delivery costs of pulpwood size wood for the different plantation management strategies, distinguished by the contribution of cultivation, harvest and transport. The conventional strategy has the lowest wood supply costs, 47 and 46 $ Mg^{-1}, followed by the additional thinning strategy, 50 and 49 $ Mg^{-1}, and 54 and 52 $ Mg^{-1} for the short rotation management strategy (without or with slash use). Using mass allocation (instead of economic allocation), total wood delivery costs increase to 54 – 60 $ Mg^{-1}. This small increase (46-54 versus 54-60 $ Mg^{-1}) of wood delivery costs is due to increased cultivation costs (not allocated to different wood classes) but lower harvest costs per dry Mg wood due to larger average d.b.h. Pulpwood delivery costs reported by other studies are in the range of 40 – 73 $ Mg^{-1} (Lu et al., 2015; Rooney & Gray, 2016), while slash delivery is between 24 and 60 $ Mg^{-1} (Rooney & Gray, 2016; Rummer et al., 2004). The loblolly pine delivery costs of pulpwood in this study can be broken down into land (17-22 %), plantation management (15-22 %), harvesting (25-31 %) and transport (31-37 %). This is in line with the cost breakdown of pulpwood supply costs reported by (Lu et al., 2015; Rooney & Gray, 2016; Rummer et al., 2004). In comparison, hypothetical production of switchgrass in the Southeastern USA has cultivation costs in the range of 40 to 70 $ Mg^{-1} (Susaeta et al., 2012b), while reported total delivery costs are in the range of 55 to 87 $ Mg^{-1} (Haque & Epplin, 2012). Thus, from an economic perspective, a combined production of biomass for wood products and energy seems favourable over producing 100 % energy crops.

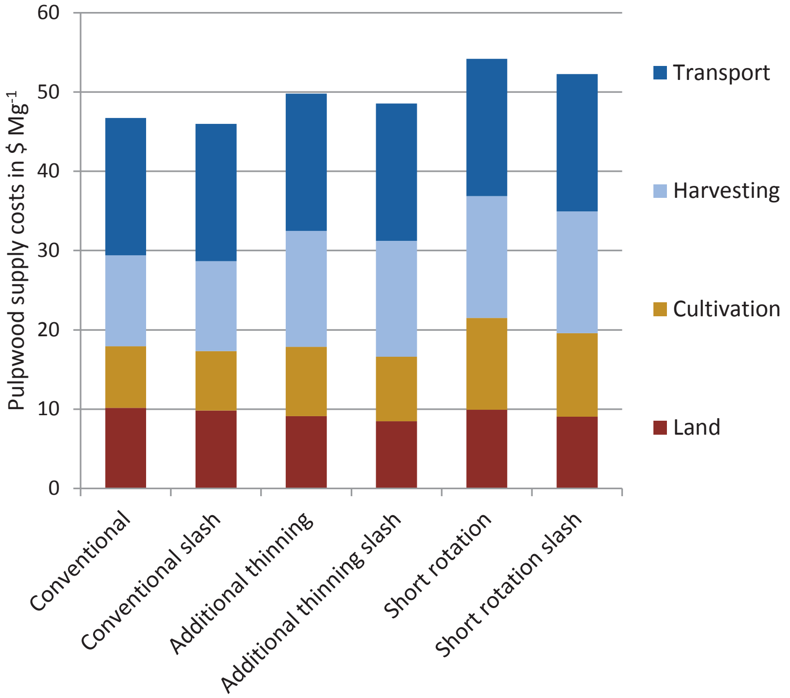

Figure 3-5, Total pulpwood supply costs of the selected loblolly pine plantation management strategies, divided by cultivation, harvest and transport of pulpwood size wood in the Southeastern USA.

Allocated cultivation costs per Mg wood for pulpwood was calculated for each plantation management strategy, as shown in Figure 3-5. The additional thinning strategy has the lowest pulpwood cultivation costs, 17.9 and 16.6 $ Mg^{-1}, followed by the conventional strategy, 17.9 and 17.3 $ Mg^{-1}, and 21.5 and 19.6 $ Mg^{-1} for the short rotation management strategy. The differences between the different plantation management strategies are low. Although the difference between the price of pulpwood and the cultivation costs is low in some cases, all plantation strategies provide a profit margin compared to the average price of pulpwood. The price of pulpwood is set to 22 $ Mg^{-1}, as specified in Table 3-4. This also implies the largest difference between cultivation costs and stumpage prices, and therefore, also the highest profit margin and net benefit for plantation owners. The most prominent difference between the different plantation management strategies is the yield of sawtimber and chip-n-saw wood. Especially for the additional thinning and conventional strategies, the allocation of a large proportion of the plantation management costs to sawtimber and chip-n-saw reduces the costs for pulpwood or slash. The product allocation is based on the classification of tree sizes, which is done with a general merchantable volume equation developed some decades ago (Yin, Pienaar, & Aronow, 1998) but is still applied in recent publications (Carlos Gonzalez-

Benecke et al., 2012; Straka, 2014). Therefore, using this approach is considered a reasonable approach to classify the harvested wood, although the amount of merchantable wood is sensitive to the diameter at harvest age t. Furthermore, the utilization of slash in the submanagement strategies increases the total wood yield and thereby reduces the allocated cultivation costs for all wood classes.

Table 3-9 also presents the (theoretical) abatement costs; a metric to show the additional costs for a plantation management strategy and the additional carbon sequestration compared to the conventional strategy. The short rotation strategy without slash utilization has no higher carbon accumulation compared to the conventional strategy and is therefore excluded from the abatement costs analysis. Furthermore, not all strategies have higher cultivation costs or higher carbon balance compared to the conventional strategy. This results in negative carbon dioxide abatement costs for the conventional with slash strategy, additional thinning strategies and the short rotation strategy with slash. Only for the short rotation with slash strategy the carbon abatement costs are positive as more carbon is sequestered after 100 years but at higher costs compared to the conventional strategy.

3.4.4 Sensitivity analysis

The sensitivity analysis was performed for the linear carbon balance (100 years) and the wood supply costs of the different plantation management strategies. The results show the impact of variation in diameter growth, total tree volume growth, the displacement factors, and the difference between the displacement factors for the different wood categories. Diameter growth has the largest impact on the total carbon balance, followed by the impact of tree volume. Both these factors have an impact on growth of pine trees and subsequently on yield and the embedded and displaced carbon. The diameter increase is especially important as it has a high impact on yield but also on the wood classification, which results in a higher displacement factor for trees with a larger d.b.h. The variation in displacement factors or the variation in the difference between the displacement factors is relatively low. As also shown in Figure 3-SI.2 the ranking of preferred plantation management strategy does not change when varying of an economic parameter, only the difference changes slightly. The economic performance is very sensitive to the diameter growth curve. For the classification in this study, only sawtimber, chip-n-saw, pulpwood and slash are considered, other wood classes like pole trees, veneer logs and others are included in sawtimber, even though these could hold higher economic value for the wood processing industry. When considering more wood classes with a higher economic value, more costs can be allocated to these classes, potentially reducing the production costs of pulpwood further. On the other hand, it remains to be seen how the quality of sawtimber and chip-n-saw products is affected by higher planting densities.

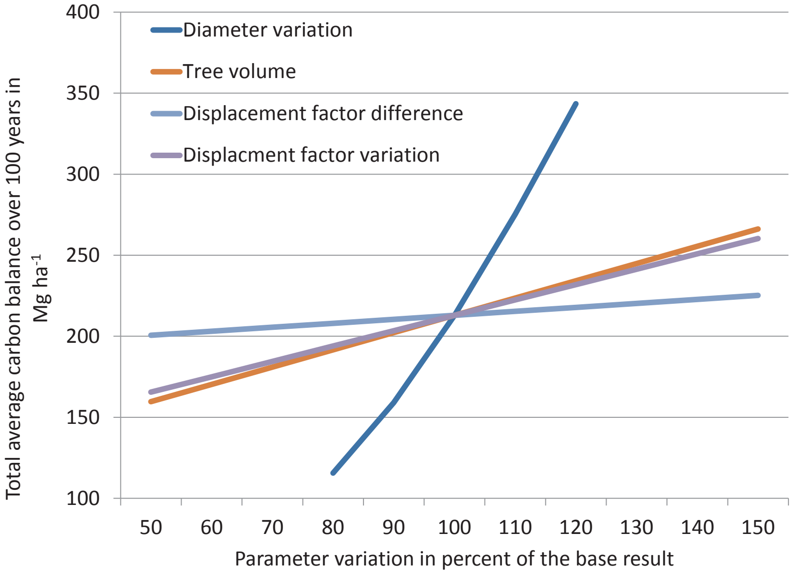

Figure 3-6 Sensitivity analysis for the total carbon accumulation after 100 years using the linear trend, for the conventional plantation management strategy when varying diameter growth, tree volume growth, displacement factors and the difference between considered displacement factors.

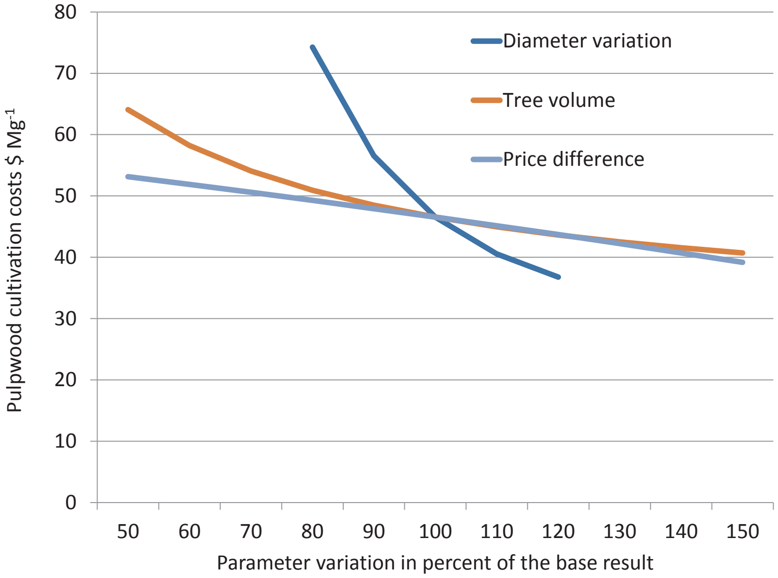

Figure 3-7 Sensitivity analysis for the pulpwood wood supply costs for the conventional plantation management strategies when varying diameter growth, tree volume growth and the price difference of the wood classes considered in this study.

3.5 Conclusion

This study evaluates the total carbon balance and economic performance of loblolly pine plantation management strategies in the Southeastern USA producing bioenergy feedstock. By doing so, this study also provides insight about how such carbon and economic analysis should be conducted and the data requirement.

The key results of this study are:

- The total net present value of the different plantation management strategies are in the range of 65 – 970 \$ ha^{-1}, with the highest value for the additional thinning strategy with slash use.
- Total wood supply costs are in the range of 46 – 54 \$ Mg^{-1} (2.7 – 3.2 \$ GJ^{-1}) and 41 – 43 \$ Mg^{-1} slash (2.4 – 2.5 \$ GJ^{-1}). The conventional strategy result in the lowest wood (pulpwood and slash for bioenergy) supply costs, as the additional thinning strategy have higher harvesting costs.
- The additional thinning strategy has the highest carbon accumulation over longer time periods, especially the additional thinning with slash utilization.

In conclusion, switching from a current conventional strategy without slash to an additional thinning strategy with using slash for bioenergy increases the overall GHG performance of the combined use of wood for products and energy over a 100 year period by about 31 %, at marginally higher wood supply cost (approximately 1.8 \$ Mg^{-1}). Furthermore, the total wood yield per hectare ranges from 8.7 to 14.1 Mg ha^{-1} y^{-1}, with the highest total yield for the short rotation management strategy with slash utilization. that the wood yield is not per se the best criteria for the selection of plantation management strategies to accumulate carbon or attain the lowest wood supply costs.

It is important to note that the results are specific for loblolly pine stands in the Southeastern USA, and may vary according to regional differences. Results are particularly sensitive to diameter growth and carbon displacement. More reliable data, especially for higher planting densities, on the diameter growth rates and carbon displacement factors will improve the robustness of the results of the economic analysis and especially the carbon balance.

The present study supports the conclusion that increased plantation management can have a positive effect on the economic performance as well as the carbon balance of loblolly pine plantations in the Southeastern USA. Furthermore, the integration of woody bioenergy use and the traditional forestry sectors leads to co-benefits in terms of cost reduction and carbon accumulation, especially for longer timeframes.

Finally, this paper solely focusses on the changing economic and GHG performances of changing management strategies. Other aspects, such as overall environmental impacts (e.g. on biodiversity, requirements to meet sustainable forest management criteria) and socio-economic impacts (e.g. possibly additional job creation) should be considered in future research.

Acknowledgement

This work was carried out within the BE-Basic R&D Program, which was granted a FES subsidy from the Dutch Ministry of Economic affairs, agriculture and innovation (EL&I). This project was co-funded by the FAPESP Bioenergy Program – BIOEN. The authors wish to thank Puneet Dwivedi of the Warnell school of Forestry and Natural resources of the University of Georgia for his suggestions to improve the manuscript. Furthermore, we thank Tom Ramsey for his contribution to the data gathering.

Supplementary information

Planning silvicultural practices

Table 3-SI.1, year of the Loblolly pine plantation management practices per strategy.

Plantation management practice	Conventional	Short rotation	Additional thinning
Site preparation, shear, rake and pile	1	1	1
Site preparation, bedding	1	1	1
Planting	1	1	1
Aerial application agrochemicals	1, 8	1, 6	1, 10, 15
Herbaceous weed control		3	3
Seedlings	1	1	1
P-fertilizers	1, 8	1, 6	1, 10, 15
N-fertilizer	8	6	10, 15
Herbicide	1	1, 3	1, 3

Table 3-SI.2 Loblolly pine plantation management characteristics, wood yield, cultivation costs and GHG emissions of pulpwood and slash production in the Southeastern USA.

		Conventional	**Conventional slash**	**Additional thinning**	**Additional thinning slash**	**Short rotation**	**Short rotation slash**
Wood yield Mg/ha-year	Total yield	8.71	9.77	10.44	12.64	11.21	14.06
	Sawtimber yield	1.85	1.85	1.62	1.62	0.04	0.04
	Chip-n-saw yield	4.21	4.21	4.22	4.22	3.46	3.46
	Pulpwood yield	2.65	2.65	4.61	4.61	7.71	7.71
	Slash yield	-	1.06	-	2.19	-	2.84
C-balance Mg carbon/ha	Year of the rotation age	176	178	175	178	201	201
	Year after rotation age	121	137	125	141	138	150
	Dynamically after 100 years	205	247	214	268	149	195
	Dynamically after 200 years	307	387	324	429	247	353
	Linear trend line after 100 year	213	244	216	259	194	242
Costs for pulpwood size wood US$/dry Mg	Allocated pulpwood costs	17.92	17.32	18.00	16.73	21.49	19.57
	Allocated slash costs	-	8.66	-	8.09	-	9.78
	Total pulpwood supply costs	47	46	50	49	54	52
	Land costs	10.15	9.81	9.10	8.46	9.92	9.03
	Land preparation costs	3.24	3.13	2.91	2.70	4.25	3.87
	Planting costs	2.42	2.34	2.74	2.55	4.01	3.65
	Herbicides costs	0.29	0.28	0.71	0.66	1.03	0.94
	Fertilizers costs	1.83	1.76	2.54	2.36	2.28	2.07
GHG emissions kg CO_2/dry Mg	Allocated GHG emissions pulpwood	3.81	3.69	3.99	3.71	7.21	6.56
	Allocated GHG emissions biomass		1.84		1.79		3.28
	Total GHG emission of wood supply	27.22	27.23	29.67	29.39	33.38	32.73
NPV US$/ha	net NPV	686	748	750	970	65	264
US$/Mg CO_2	CO_2 abatement costs	-	-8	-8	-12	-	21

Sensitivity analysis all loblolly pine plantation management strategies

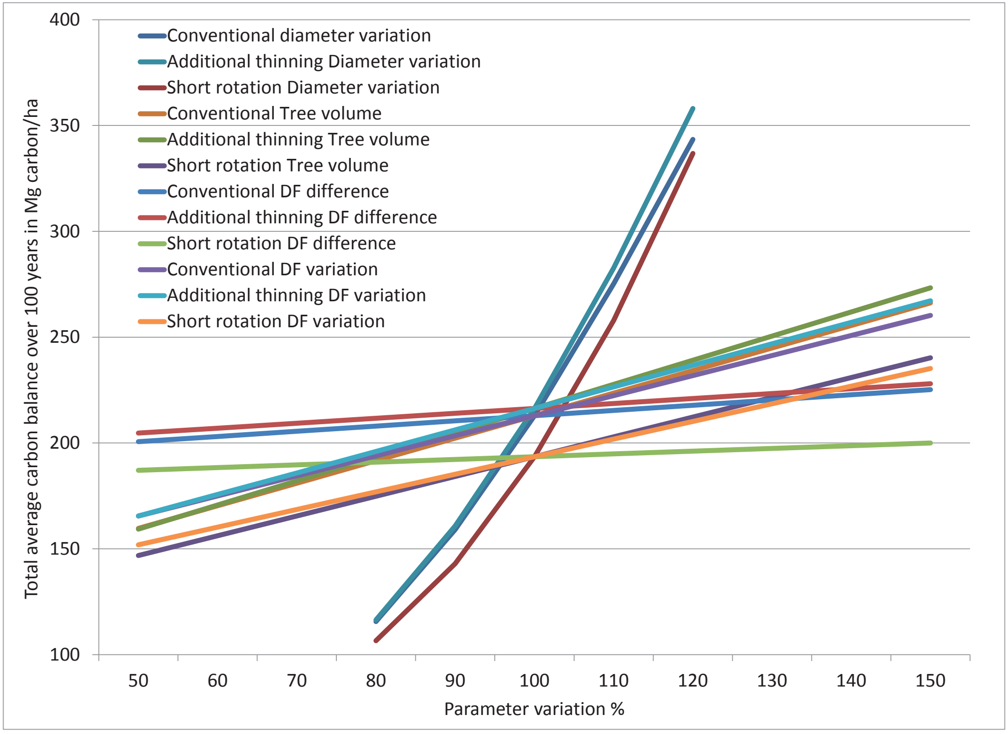

Figure 3-SI.1 Sensitivity analysis for the total average carbon balance, linear trend, for the conventional plantation management strategy when varying diameter growth, tree volume growth, displacement factors and the difference between considered displacement factors.

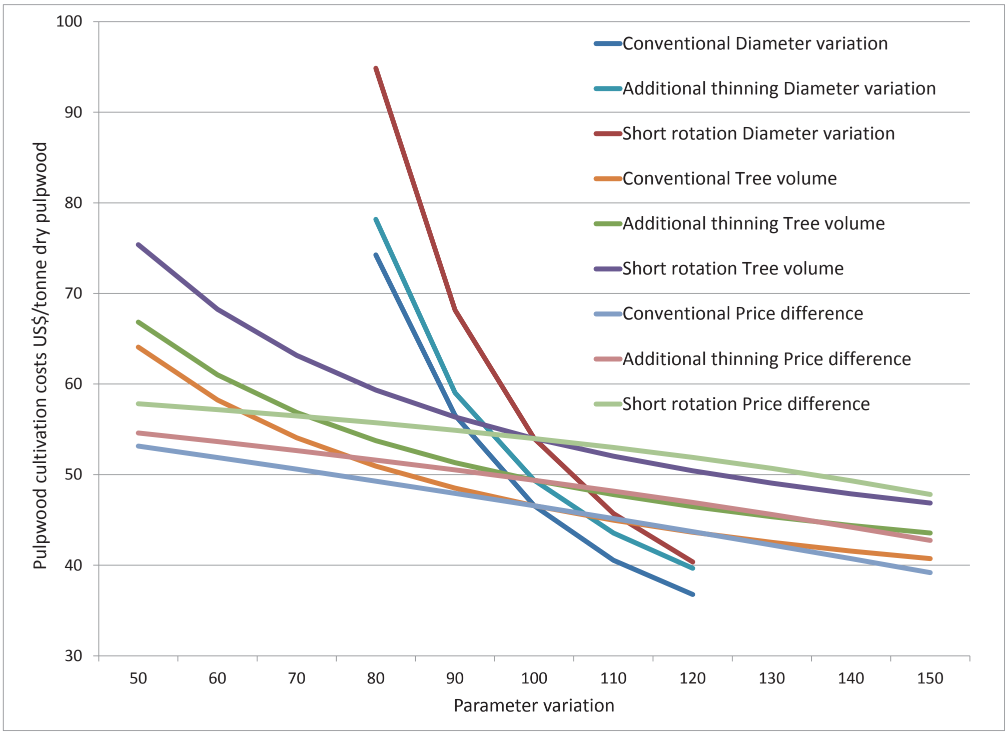

Figure 3-SI.2 Sensitivity analysis for the pulpwood total wood supply costs for the conventional plantation management strategy when varying diameter growth, tree volume growth and the price difference of the wood classes considered in this study.

Chapter 4

Outlook for ethanol production in Brazil up to 2030, for different biomass crops and industrial technologies

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Abstract

This paper presents an economic outlook of the ethanol industry in Brazil considering different biomass feedstocks and different industrial processing options. A spreadsheet model was designed to account for different feedstocks and industrial processes, and expected trends in biomass yield, sugar- and fibre content, industrial scale and efficiency. Sugarcane and energycane cultivation costs may be reduced from 35 US$$_{2010}$/TC in 2010 to 27 US$$_{2010}$/TC and 22 US$$_{2010}$/TC in 2030 respectively. Eucalyptus and elephant grass cultivation costs could be reduced from 32 to 23 US$$_{2010}$/tonne wet and 38 to 26 US$$_{2010}$/tonne wet for eucalyptus and elephant grass. Total ethanol production costs of first generation processing may decrease from 700 US$$_{2010}$/m^3 in 2010, to 432 US$$_{2010}$/m^3 in 2030. First generation ethanol production costs may decrease by reduced feedstock costs, increase in sugar content, utilization of cane trash, and use of sweet sorghum. Furthermore, the improvement in industrial efficiency of the first generation process, increasing industrial scale and change to an improved technology are other measures. For second generation technology utilizing eucalyptus, the total ethanol production costs could be strongly reduced to 424 US$$_{2010}$/m^3 in 2030. Costs reduction measures for second generation industrial processing include reduced feedstock costs, increasing industrial efficiency and scale, and a change to more advanced industrial process. Overall, biomass yield, increase in sugar content of sugarcane, and improved industrial efficiency are important parameters in total ethanol production costs. Ongoing RD&D effort and commercialization of second generation industrial processing may result in the lowest ethanol production costs for second generation processing in the future.

4.1 Introduction

In recent decades worldwide biofuels production and consumption expanded significantly due to supportive policies aiming to, among others, reduce greenhouse gas (GHG) emissions and diversifying energy sources (H. Chum et al., 2011; IEA, 2010). It is expected that the biofuel demand will increase further in the coming years (IEA, 2013a). Of the total world biofuel demand, 2.9 EJ (IEA, 2013b), around 2.0 EJ was ethanol in 2011 (H. L. Chum et al., 2013). In the past decades, Brazil and the USA have dominated the ethanol production worldwide (Lamers et al., 2011). Up to today, Brazilian ethanol production is primarily based on the fermentation of extracted sugars from sugarcane (Carioca & Leal, 2011), and production reached almost 0.47 EJ in 2011 (Chum et al. 2013). The sugarcane output originates predominantly (around 90%) in the Centre-South region of Brazil (J. Seabra et al., 2011).

Brazil has the potential to expand its ethanol production in the future (Cerqueira Leite, Verde Leal, Barbosa Cortez, Griffin, & Gaya Scandiffio, 2009; H. Chum et al., 2011; Lamers et al., 2011). Potential options include the expansion of cultivation area, improvement in agricultural or industrial yield and the introduction of new industrial processing pathways (BNDES, 2008; Cerqueira Leite et al., 2009; Lamers et al., 2011; van den Wall Bake et al., 2009; Walter, 2008). New industrial processing pathways could include improved first generation (fermentation of sugars) or second generation (conversion of lignocellulosic biomass) industrial processing. Second generation industrial processing would enable the conversion of lignocellulosic biomass feedstocks, like woody biomass, perennial grasses and agricultural or industrial by- products. The implementation of second generation technology could strongly improve the ethanol production per hectare by using these lignocellulosic by-products of sugarcane processing (Matsuoka, Ferro, & Arruda, 2009; Soccol et al., 2011). Furthermore, the use of second generation technology could enable year-round ethanol production, as the supply of lignocellulosic crops is less seasonable than sugarcane. Despite the ongoing research in 2nd generation technology, the economic performance of future technology developments remains uncertain (Chovau et al., 2013). Next to sugarcane, other biomass feedstock have been proposed for ethanol production due to their potential yield, composition or tolerance to climate and/or soil characteristics in other cultivation areas (BNDES, 2008; Gonzalez, Treasure, Wright, et al., 2011; Reddy, Ramesh, & Reddy, 2005; Somerville, Youngs, Taylor, Davis, & Long, 2010). Especially, the development of second generation industrial processing would enable the utilization of more biomass feedstocks.

With the ongoing research and development in biomass cultivation of different ethanol feedstock and industrial processing pathways the ethanol production costs are likely to change in the future. This study focusses on the current and future ethanol production cost in Brazil, considering the utilization of different production configurations[3]. Ethanol

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[3] In this research, the term ‘configuration’ is used to indicate a combination of biomass feedstock (or multiple feedstocks) and industrial processing route; which could be first generation, second generation or a combination of first and second generation technologies.

production in Brazil is primarily based on sugarcane; no significant ethanol production is based on other feedstock (BNDES, 2008). Other potential ethanol production biomass feedstock include, among others, energycane (Kim & Day, 2011; Leal, Walter, & Seabra, 2012), sweet sorghum (Almodares & Hadi, 2009; Reddy et al., 2005), elephant grass (or other perennial grasses) (BNDES, 2008; Eliana, Jorge, Juan, & Luis, 2014) and eucalyptus (González-García, Moreira, Feijoo, & Murphy, 2012; Gonzalez, Treasure, Phillips, et al., 2011).

Sugarcane cultivation costs have been investigated by multiple studies, among others XAVIER, SONODA, ZILIO, & MARQUES, (2010) Eduardo & Xavier, (2012) van den Wall Bake et al., (2009). Energycane is a high-yielding sugarcane variety with a potential higher total biomass yield, lower sugar content but high fiber content (Leal et al., 2012). The main advantage of sweet sorghum as ethanol feedstock is the harvest period is outside the harvesting season of sugarcane (BNDES, 2008). Cultivation costs of sweet sorghum have been investigated by Reddy et al., (2005) Koppen, Reinhardt, & Gartner, (2009). Both eucalyptus and elephant grass have been indicated as potential (lignocellulosic) feedstock for ethanol production with second generation technology (BNDES, 2008; Gonzalez, Treasure, Phillips, et al., 2011; Hamelinck et al., 2005). Eucalyptus is a fast growing woody biomass, cultivated in Brazil for wood and paper production (Stape et al., 2010). Eucalyptus cultivation costs have been estimated by Florestal, Eucalipto, José Luiz Pereira, Rezende, Cláudio Túlio Jorge, Padua, Antônio Donizette, & Scolforo, (2006) Laurent Marie Roger Quéno, Álvaro Nogueira de Souza et al., (2011) Gonzalez, Treasure, Wright, et al., (2011). Elephant grass cultivation costs are reported by Laurent Marie Roger Quéno, Álvaro Nogueira de Souza et al., (2011). The above mentioned publications dealing with biomass cultivation cost indicated that biomass yield improvement and change of cultivation management practices are key issues for biomass cultivation costs reduction.

Potential ethanol production pathways can, in general, be classified into 3 main options: first generation, second generation and integrated first-and-second generation industrial processing. Numerous studies identified the current and future technical and economic performance of sugarcane first generation processing Dias, Cunha, et al., (2011); Dias, da Cunha, et al., (2011); van den Wall Bake et al., (2009); Walter, (2008). The conversion of lignocellulosic feedstock like eucalyptus, elephant grass and cane bagasse or trash with second generation processes have been assessed by different studies Hamelinck et al. (2005); Soccol et al. (2010); Dias et al. (2012); Gonzalez, Treasure, Phillips, et al. (2011); Schmer et al. (2008). Also the utilization of sugarcane in integrated first-and-second generation industrial processes has been researched for ethanol production Dias et al., (2012), (2013); Dias, da Cunha, et al., (2011); Macrelli, Mogensen, & Zacchi, (2012). Overall these authors indicated that the industrial efficiency improvement and / or change of conversion technology or improvement of technology set-up are key factors affecting industrial processing costs.

The objective of this paper is to examine the potential development in future ethanol production costs in Brazil, up to 2030, given the technical and economic development of biomass feedstock cultivation and industrial processing of first and second generation technologies. To our knowledge no detailed and comparative supply chain analysis has been performed determining the total ethanol production costs in Brazil, taken into account different biomass feedstock and different industrial processing routes. The goal is to provide a bottom-up economic assessment of different combinations of biomass feedstock and ethanol processing routes, resulting in the total ethanol production costs of different configurations and for different settings. A uniform comparison of different potential feedstock for ethanol production could guide future research, support political debate and private investors in the Brazilian ethanol industry.

4.2 Industrial processing pathways for ethanol production

In general, three main ethanol conversion technologies can be distinguished: a first generation process, a second generation process and an integrated of first-and-second generation conversion processes. First generation industrial processing is the conversion of sugar- or starch-rich biomass crops to ethanol. In sugar based first generation industrial process (see Figure 4-1a) sugarcane, energycane or sweet sorghum is shredded and milled to extract the sugar-rich juice. The sugar juice is treated and concentrated[4] by evaporation before entering the fermentation step (Macrelli et al., 2012). During fermentation (an exothermic process) sucrose is converted to glucose and fructose, which are converted[5] to ethanol, CO_2 and by products (alcohols, organic acids, etc.) (Dias, da Cunha, et al., 2011). The fermented broth is fed to a centrifuge to enable yeast separation and recovery. The fermentation gasses are fed to an absorber for ethanol recovery (Dias, Modesto, et al., 2011). Both the ethanol recovered from the centrifuge and absorber are fed to a distillation column. The distillation product is fed to a rectification column which produces hydrous ethanol. After further dehydration anhydrous ethanol is formed. For first generation technologies, cane-bagasse[6] and cane-trash[7] are fed to a cogeneration facility to produce process steam and process / surplus electricity.

Second generation industrial processing (see Figure 4-1b) is the conversion of lignocellulose biomass to ethanol. Due to the complex structure of lignocellulose, the biomass needs to undergo treatment before embedded sugars are available for the fermentation to ethanol. In a second generation industrial process, lignocellulosic biomass

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[4] As the sucrose concentration is too low (13.7 wt-%) to reach the preferred ethanol concentration in the fermentation stage, an evaporation unit is used to increase the concentration to 19 wt-% (Macrelli et al., 2012).

[5] Fermentation can be presented by the simplified chemical equations (Carioca & Leal, 2011):

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \quad \text{and} \quad C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 23.5\ kcal$$

[6] Cane bagasse is the by-product of sugarcane first generation process. After sugar extraction, a fibrous material remains which can be used for steam and electricity production or ethanol production

[7] Cane trash is a residue of sugarcane harvesting, and consists of the dry and green leaves of the sugarcane plant. During harvesting the sugar-rich cane-stalks are considered the main product, which are loaded and transported to the industrial processing plant. Cane trash is left on the field, unless it is collected, loaded and transported for use in the industrial plant.

feedstock is pre-treated, the hemicellulose and very little cellulose are hydrolysed, followed by fermentation and ethanol separation (Chovau et al., 2013; Soccol et al., 2011). Hydrolysis combined with fermentation is more complex than fermentation of simple sugars (Hamelinck et al., 2005). Many different techniques to pre-treat and hydrolyse the lignocellulose biomass have been researched to improve ethanol yield and reduce ethanol production costs (Macrelli et al., 2012). Currently, steam pretreatment followed by enzymatic hydrolysis is considered as one of the most viable options for lignocellulosic ethanol production (Macrelli et al., 2012). The industrial processing residues of the second generation process, which mainly consist of the lignin and un-reacted cellulose from hydrolysis are fed to the cogeneration facility.

Another possibility is to integrate first-and-second generation processes: the lignocellulosic residues of the first generation process (bagasse and trash) are fed to the second generation process, see Figure 4-1c. The cogeneration unit, fed with residues of the second generation process, supplies the steam and electricity for both processes.

The selected configurations in this study include two first generation industrial processes, two second generation processes and two integrated first-and-second generation processes. For first generation processing a currently applied technology, using conventional dehydration (azeotropic distillation) with low pressure steam cycle, and an optimized technology utilizing molecular sieves and high pressure boilers are taken into account. The use of molecular sieves and high pressure boilers results in higher equipment costs, but also results in higher electricity surplus. For second generation the basic technology comprises of steam explosion (SE) pretreatment and enzymatic hydrolysis with bought enzymes for simultaneous saccharification and fermentation. The optimized second generation process comprises of liquid hot water (LHW) pretreatment, followed by enzymatic hydrolysis (with on-reactor enzyme production) and fermentation in a consolidated bioprocessing unit. In Table 4.1 an overview is given of the main features of the different industrial processing pathways. The integrated first-and-second generation plants combines the optimized first generation process with steam explosion pretreatment or liquid hot water pretreatment for second generation processing.

Table 4-1 Main differences in the different industrial processing pathways.

Main features	**Basic first generation**	**Optimized first generation**	**Basic second generation**	**Optimized second generation**
Prime feedstock	Sugarcane, energycane, sweet sorghum[B]		Lignocellulosic biomass (eucalyptus or elephant grass) or first generation residues	
Sugar extraction and mobilization	Shredder	Shredder	Steam explosion (SE) pretreatment	Liquid Hot Water (LHW) pretreatment
Fermentation	Fermentation reactor vessel	Fermentation reactor vessel	Simultaneous Saccharification	Consolidated bioprocessing

			and co-Fermentation	
Ethanol dehydration	Conventional	Molecular sieves	Molecular sieves	Molecular sieves
Cogeneration unit	Lower pressure boiler	High pressure boiler	High pressure boiler	High pressure boiler
Abbreviation		**Feedstock**	**First generation technology**	**Second generation technology**
Basic 1G sugarcane		Sugarcane	Basic	
Basic 1G energycane		Energycane	Basic	
Optimized 1G sugarcane		Sugarcane	Optimized	
Optimized 1G sugarcane + trash		Sugarcane, cane trash	Optimized	
Optimized 1G sugarcane + trash + sweet sorghum		Sugarcane, cane trash, sweet sorghum	Optimized	
Optimized 1G energycane + trash + sweet sorghum		Energycane cane trash, sweet sorghum	Optimized	
Basic 2G eucalyptus		Eucalyptus		Basic
Basic 2G elephant grass		Elephant grass		Basic
Optimized 2G eucalyptus		Eucalyptus		Optimized
Optimized 2G elephant grass		Elephant grass		Optimized
Sugarcane 12G basic		Sugarcane	Optimized	Basic
Sugarcane 12G optimized		Sugarcane	Optimized	Optimized
Sugarcane 12G optimized + trash		Sugarcane, cane trash	Optimized	Optimized
Sugarcane + sweet sorghum 12G optimized + trash		Sugarcane, cane trash, sweet sorghum	Optimized	Optimized
Sugarcane + sweet sorghum 12G optimized + trash 300 days[A]		Sugarcane, cane trash, sweet sorghum	Optimized	Optimized

[A] This configuration incorporates the storage of bagasse. Available cane trash is used during harvest season of sugarcane, outside the harvest season the available bagasse is utilized. The scale of the second generation process is scaled on the highest scale needed to process the trash during sugarcane harvest season, or available bagasse outside the harvesting season. The total operational time of the plant is maximal 300 days.

[B] Sweet sorghum is only used as complementary feedstock, meaning sweet sorghum is only cultivated on fallow cane-land, between two cane cycles (between the last ratoon and replanting).

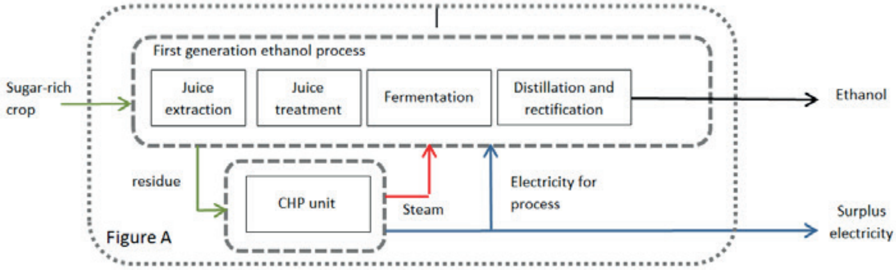

Figure A

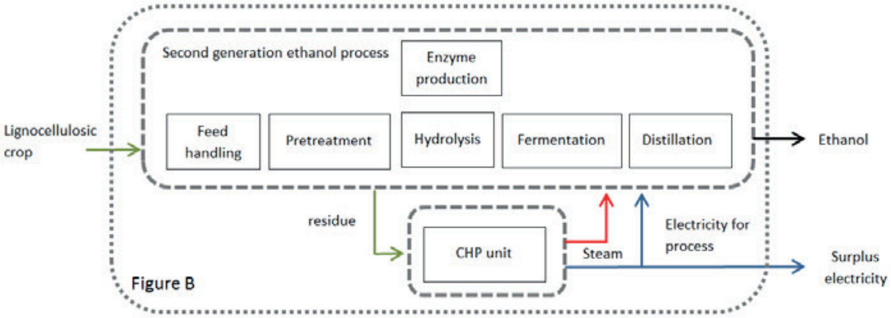

Figure B

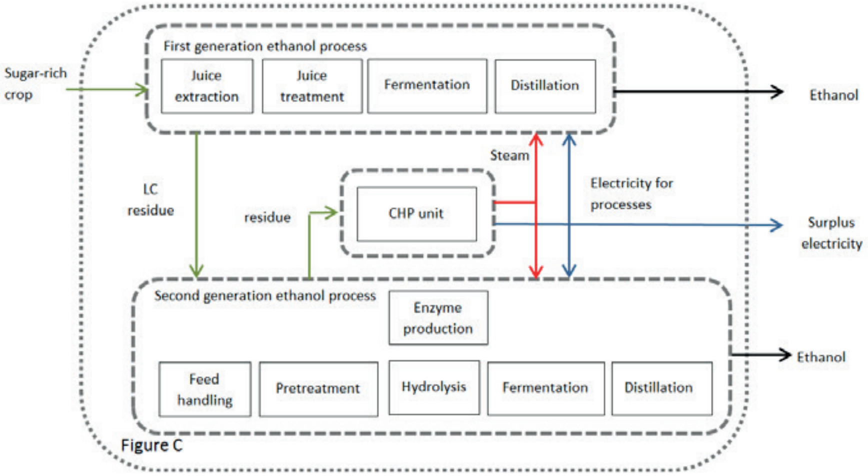

Figure C

Figure 4-1 Schematic overview of possible ethanol conversion concepts; 1A First generation technology, 1B Second generation technology, 1C Combined first-and-second generation technology.

4.3 Methods

The production cost assessment of ethanol involves three main steps: biomass feedstock cultivation (including harvest), transport, and industrial processing to ethanol. Various parameters may affect total ethanol production costs, e.g. agricultural yield, biomass composition, industrial processing scale and industrial efficiency. For biomass cultivation, transport and industrial processing a bottom-up cost assessment is performed, making a distinction between different cost elements, e.g. capital, labour, cultivation inputs, raw materials and other expenses. A spreadsheet model is constructed to calculate the bottom-up current and future cost structure of feedstock cultivation, transport and industrial processing. The total ethanol production cost, (expressed in US$$_{2010}$/m^{3}ethanol for each configuration) is determined for the best available technology of each configuration, for each year between 2010 and 2030. A net present value (NPV) approach was used, to account for fluctuating expenses and benefits over a lifetime of a plantation or industrial plant.

4.3.1 Disaggregated current ethanol production costs

4.3.1.1 Biomass cultivation costs

Within the spreadsheet model, the cultivation costs of sugarcane, energycane, sweet sorghum, eucalyptus and elephant grass are determined. The spreadsheet model incorporates a database of all management practices or inputs used in the cultivation of all five biomass crops, based on a spreadsheet model called CanaSoft developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) in Brazil (CTBE, 2012) and on available literature. All management practices and cultivation inputs are calculated on a per hectare basis except for the cost of harvesting and fertilizers, which are related to the biomass yield. The total biomass cultivation costs (US$$_{2010}$/tonne biomass feedstock) are assessed by calculating the NPV or all costs items and the yield during the cultivation period. The biomass cultivation costs are, similar to (Floor Van Der Hilst & Faaij, 2012) determined using Equation 1:

$$\text{Biomass cultivation cost} = \frac{\sum_{y=1}^{y=x} \frac{\sum_{n=1}^{N}\left(O_{ny} \times C_{ny}\right) + \sum_{m=1}^{M}\left(O_{my} \times C_{my} \times \text{Yield}_y\right)}{(1+a)^y}}{\sum_{y=1}^{y=x} \frac{\text{Yield}_y}{(1+a)^y}}$$

Equation 1

Item	**Description**	**Unit**
Biomass cultivation costs	Discounted costs feedstock production	US$/tonne
O_{NY}	Occurrence cost item per ha$_n$ in year y	#
C_{NY}	Cost of cost item n in year y	US$/ha
O_{MY}	Occurrence of cost item per tonne m in year y	#
C_{MY}	Costs of cost item m per tonne	US$/tonne

Yield_Y	Yield in year y	tonne/ha
a	Annuity rate	12%
y	Annuity period	years

4.3.1.2 Biomass transport costs

Biomass transportation costs are mainly driven by the transport distance, which is determined by industrial capacity (annual input), yield of the biomass feedstock and a factor to account for the spatial distribution of biomass cultivation fields and accessibility, similar to Leboreiro & Hilaly, (2011). This factor remains constant for the different configuration and is based on the current average transport distance for industrial processing plants in Brazil, yield and capacity. As the investment cost of truck and trailer are already discounted over the lifetime of the truck and trailer, and all other are operational expenses, the elements in Equation 2 are not discounted. The cost data for truck and trailer investment, operational expenses and other costs components is based on (CTBE, 2012). The amount of delivered biomass truck loads per day is determined by dividing the daily operational time of a truck by the total time needed for a return trip: sum of distance divided by average speed and loading and unloading time. Diesel consumption is determined by the transport distance and diesel consumption per km. See Equation 2 for the transport costs calculation: more information about the individual items is given in supportive information SI 3.

$$\text{Transport costs} = \frac{\frac{\text{De}}{\text{T}} + \text{La} + \left(\left(\frac{(\text{TD})}{\text{Di}}\right) \times \text{Dc}\right) + \text{Ma} + \text{Ti} + \text{Lu}}{\text{Lo}}$$

Equation 2

Item	**Description**	**Unit**
Transport costs	Biomass transport costs	US$/tonne
De	annualised depreciation costs of capital investment of a truck + trailer	[US$/year]
T	amount of return trips a truck can make in a year	[trips/year]
La	labour costs for truck operation	[US$/trip]
TD	averaged distance of return trip between biomass cultivation field and industrial processing plant	[km/trip]
Di	diesel consumption	[km/l]
Dc	diesel costs	[US$/l]
Ma	costs for truck and trailer maintenance	[US$/trip]
Ti	annualised costs of tires	US$/year
Lu	costs for lubricants	[US$/trip]
Lo	truck load capacity	[tonne/truck load]

4.3.1.3 Total ethanol industrial processing costs

The industrial processing costs consist of the capital expenses, operational costs, maintenance, labour and electricity expenses or revenues. Investment costs of the industrial plant (including cogeneration unit) is a sum of the major equipment costs and costs for installation, building and engineering etc. Considering an increasing scale, the scale of the individual components will be scaled up with relevant scaling factors. The equipment costs, including scale factors and maximum scale can be found in section 4.4.3. Operational expenses are all expenses to operate the industrial facility, for example chemicals used and other consumables. The operational and labour expenses of the first generation processes or second generation processes can be found in SI.6 of the supplementary information. Maintenance expenses are all costs needed to maintain the plant, this includes replaced equipment and labour costs, see supplementary information SI.6.

$$\text{Industrial cost} = \frac{\sum_{y=1}^{y=x} \frac{\sum(\mathrm{E} \times \mathrm{I}) + \mathrm{En} + \mathrm{O_{ny}} + \mathrm{La_{ny}} + \mathrm{Ma_{ny}} + \mathrm{Ad_{ny}} - \mathrm{Elec_{ny}}}{(1+\mathrm{a})^{\mathrm{y}}}}{\sum_{y=1}^{y=x} \frac{\mathrm{Ethanol_y}}{(1+\mathrm{a})^{\mathrm{y}}}}$$

Equation 3

Item	**Description**	**Unit**
Industrial cost	Industrial processing cost	US$/m^3 ethanol
E	Equipment costs of individual industrial component	[US$]
I	Installation factor to account for installation and auxiliary equipment	[US$]
En	Engineering costs for total installation	[US$]
$\mathrm{O_{ny}}$	Operational expenses	[US$]
$\mathrm{La_{ny}}$	Labour costs for operational staff	[US$]
$\mathrm{Ma_{ny}}$	Operation and maintenance costs (other than operational expenses	[US$]
$\mathrm{Ad_{ny}}$	Administration expenses	[US$]
$\mathrm{Elec_{ny}}$	Electricity revenues	[US$]
a	Annuity rate	12%
$\mathrm{Ethanol_Y}$	Annual ethanol yield in year Y	[m^3 ethanol]
Y	years	year

The ethanol yield of the industrial process is based on available sugars, extraction of sugars and the conversion efficiencies to ethanol. Given Equation 4, the ethanol yield, expressed in m^3 of ethanol per tonne of wet cane or sweet sorghum from the first generation sugar-to-ethanol conversion process is formulated as follows:

$$\text{Ethanol yield 1G} = \frac{(\text{TRS} \times \eta_{\text{Ex}} \times (1 - \eta_{\text{sl}}) \times \eta_{\text{Fer}} \times \eta_{\text{Di}}) \times \text{Cmax}}{\text{Ethanol density}}$$

Equation 4

Item	**Description**	**Unit**
Ethanol yield 1G	Ethanol yield of first generation industrial processing	m^3ethanol/tonne wet biomass
TRS	Sugar content in biomass feedstock	[kg/tonne wet]
η_{Ex}	Sugar extraction efficiency	[%]
η_{sl}	Sugar losses cane washing	[%]
η_{Fer}	Fermentation efficiency	[%]
η_{Di}	Distillation efficiency	[%]
Cmax	Stoichiometric conversion factor sugar to ethanol	[0.51 kg EtOH/kg sugar]
Ethanol density	Ethanol density	[790 kg/m^3]

For second generation technology the ethanol yield is the sum of the ethanol yield per polysaccharides flow. Given the chemical composition of the lignocellulosic feedstock and the conversion efficiency of polysaccharides to monosaccharide's and the conversion efficiency of monosaccharide's to ethanol, see Equation 5:

$$\text{Ethanol yield 2G} = \frac{\sum\Big(\Big(\big(\text{Sugar} \times \eta_{\text{Poly-mono}} \times \text{factor}\big) - \text{enzymes}\Big) \times \eta_{\text{mono-ethanol}} \times \text{Cmax}\Big)}{\text{Ethanol density}}$$

Equation 5

Item	**Description**	**Unit**
Ethanol yield 2G	Ethanol yield of second generation industrial processing	m^3ethanol/tonne dry biomass
Sugar	Amount of C_5 or C_6 sugar in the respective feedstock	[kg/tonne dry]
$\eta_{\text{Poly-mono}}$	Conversion efficiency of polysaccharides to monosaccharides	[%]

Factor	Stoichiometric conversion factor polysaccharides to monosaccharides[8]	[-]
Enzymes	Sugar consumption by enzymes	[kg]
$\eta_{\text{mono-ethanol}}$	Conversion of monosaccharides to ethanol	[%]
Cmax	Stoichiometric conversion factor sugar to ethanol	[0.51 kg EtOH/kg sugar]
Ethanol density	Ethanol density	[790 kg/m^3]

$$\text{enzymes} = \text{consumption } \times \text{ethanol yield}$$

Equation 6

Item	**Description**	**Unit**
Enzymes	Sugar consumption by enzymes	[kg/tonne biomass]
Consumption	Consumption of sugar by enzymes[9]	kg/m^3 ethanol
Ethanol yield	Ethanol yield (determined with formula 5, but without enzyme consumption)	m^3 ethanol/tonne biomass

The electricity surplus is based on the steam cycle (boiler, turbine, condenser and boiler feed pump), including steam extraction point, whereas the work delivered in the turbine is the enthalpy difference in the turbine (Cengel & Boles, 2011). The surplus electricity is determined based on the energy embedded in the residues fed to the cogeneration unit, boiler efficiency, steam and electricity demand for the ethanol production process, see Equation 7. The electricity surplus is based on the energy flow out of the boiler (Equation 8), minus the energy embedded in the steam (for process steam) and the energy leaving the turbine, after steam expansion in the turbine.

$$\text{Electricity surplus} = \frac{\text{E}_{\text{ab}} - \text{E}_{\text{sc}} - \text{E}_{\text{at}}}{3.6} - \text{own elec use}$$

Equation 7

Item	**Description**	**Unit**
Electricity surplus	Electricity surplus for grid supply	kWh
E_{ab}	Energy embedded in steam (high pressure, high	MJ

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[8] Conversion of C_5 polysaccharides (xylan and arabinan) to monosaccharides is assumed to have a conversion factor of 1.136, while C_6 sugars chains (glucan, galactan and mannan) are converted with a ratio of 1.111 (Chovau et al., 2013; McMillan, 1993). The conversion efficiency of polysaccharides to monosaccharides is expressed as percentage of the maximum theoretical yield; which is 1.136 and 1.111 for C_5 and C_6 sugars, given the conversion reactions given by (Chovau et al., 2013)

[9] consumption per kg ethanol; 6.3 g sugars 9.3 g cellulose (Hamelinck et al., 2005)

	temperature)	
E_{sc}	Energy embedded in steam for own use	MJ
E_{at}	Energy flow embedded in steam after turbine (low pressure, low temperature)/	MJ
Own elec use	Own electricity use	kWh
3.6	Conversion MJ/kWh	MJ/kWh

$$E_{\text{after boiler}} = \frac{\text{Boiler feed } \times \text{HHV} \times \eta\text{boiler}}{\Delta\text{H Boiler}} \times \Delta\text{Hsteam}$$

Equation 8

Item	**Description**	**Unit**
Boiler feed	Flow of available residues (boiler feed)	[kg]
HHV	Higher heating value residues	[MJ/kg]
ηboiler	Efficiency boiler	[%]
ΔH boiler	Heat content change in boiler (difference feed water and steam leaving boiler)	[MJ]
ΔH steam	Heat content steam after boiler	[MJ]

4.3.2 Future outlook for total ethanol production costs

As the biomass yield, composition of the biomass feedstock, conversion efficiencies and scale of the industrial plant are expected to change over time, the total ethanol production costs change as well. A future outlook of the total ethanol production costs should incorporate the potential trend of the most important variables. The variables considered in this study are the biomass agricultural yield, sugar- and fiber content of sugarcane, energycane and sweet sorghum, ethanol production efficiency of the first and second generation processes and the scale of the industrial plant. For each year between 2010 and 2030 the input parameters are determined and applied in the above mentioned Equations 1-8. For the input parameters the current value and the potential trend in the future is based on literature and expert opinion. This gives insights in the potential future ethanol production costs of the best available technologies for the different configurations up to 2030. Section 4.4 provides an overview of the data input required and the trend for the different variables.

4.3.3 Sensitivity analysis

A sensitivity analysis is performed on the different ethanol production configurations in 2030. The potential effect of biomass yield, ethanol industrial yield, capital investment, fertilizer prices and electricity revenues on ethanol production cost is considered. Historically, yield has been the main driver for the observed trend in cultivation costs of sugarcane (van den Wall Bake et al., 2009) and eucalyptus (de Wit, Junginger, & Faaij, 2013). Similar to agricultural yield, the industrial yield (ethanol yield) is an important driver for total ethanol production costs, due to its crucial role in Equation 3. Next to feedstock costs, the capital expenses are indicated as another major cost component in total ethanol production costs (Humbird et al., 2011; van den Wall Bake et al., 2009), especially for second generation technology (Chovau et al., 2013; Humbird et al., 2011). Electricity revenues also play an important role in total ethanol production costs as electricity surplus can be as high as 2 kWh_e/L ethanol for first generation technology or 0.85 kWh_e/L ethanol for integrated first-and-second generation technology (Dias, Cunha, et al., 2011). For the economically most interesting options for first-, second and first-and-second generation technology a sensitivity analysis is performed and presented in a spider diagram by varying the selected parameters.

With the potential expansion of cultivation area in Brazil, biomass feedstock cultivation may expand to regions more or potentially less suitable for certain biomass crops, compared to São Paulo state. Yield may be affected by agro-ecological suitability and therefore, total ethanol production cost may vary between regions. As land cost in São Paulo are much higher compared to other regions (Gasques, Bastos, & Valdes, 2008), the expansion of cultivation area may lead to lower cultivation costs as land costs are reduced. In Figure 4-2, the potential expansion areas of Mato Grosso do Sul (dark grey) and Mato Grosso (light grey) are presented, next to São Paulo state (black). This potential expansion is derived from (Cerqueira Leite et al., 2009). To provide more insight in the potential of different configurations in regions outside of São Paulo state a regional analysis is performed. Such regional analysis includes the potential yield ranges of biomass feedstocks and potential land prices of the respective regions.

Figure 4-2 Current dominant sugarcane cultivation area (São Paulo) and potential expansion areas for biomass cultivation in Brazil.

4.4 Data input

4.4.1 Biomass cultivation

Sugarcane is cultivated in a cycle[10] of 6 years, with 5 harvestings, starting 12-18 months after planting (El Bassam, 2010), each harvest yield is reduced compared to previous one[11]. Around 8.6 Mha of sugarcane was harvested in 2009 (MINISTÉRIO da, AGRICULTURA, & MAPA, 2010). In the supportive information an overview of management practices and cultivation inputs are given for sugarcane and energycane. Energycane is a high yielding (high fibrous) group of sugarcane varieties, it is therefore assumed to follow a similar cultivation management cycle and cultivation techniques. In this outlook we consider the use of the ETC harvesting machine, next to conventional harvesting machine and manual harvesting system (the latter being currently replaced by mechanical harvesting[12]). The ETC machine is currently under development at the Brazilian Bioethanol Science and Technology Laboratory (CTBE), capable of performing harvesting and planting operations (Bonomi et al., 2011; CTBE, 2014; Júnior, Leal, & Luís Augusto Barbosa Cortez Leite, 2009). Sweet sorghum can be cultivated in various regions due to its adaptability, rapid growth, sugar accumulation, drought tolerance, tolerance to water logging and tolerance to acidity toxicity (Almodares & Hadi, 2009; El Bassam, 2010). The cultivation period of sweet sorghum is around 120-130 days, with one final harvest (Almodares & Hadi, 2009; Koppen et al., 2009). No information was found on the cultivation area of sweet sorghum in Brazil. In this we assume the use of harvesting machines for sweet sorghum similar to sugarcane. Eucalyptus is cultivated in ratoon cycles of 7 years, with a plantation renewal after the third harvest (21 years). Yield levels are described as averaged annual yields, commonly expressed in cubic metre per hectare. In 2009, eucalyptus occupied 4.5 Mha of land in Brazil (Laércio Couto, 2011). Selected harvesting equipment is typical for harvesting of woody biomass; harvesting costs are expressed per m^3 of harvested eucalyptus. Elephant grass can be harvested twice a year, apart from first year after plantation establishment, with the time before renewing the site up to 20 years (Laurent Marie Roger Queno, Alvaro Nogueira de Souza, Humberto Angelo, Aitlton Teixeira do Vale 2011). In Table 4-2 an overview is given of current yield of all biomass feedstock and the sugar- and fibre content of sugarcane, energycane and sweet sorghum in the state of Sao Paulo. The chemical composition of eucalyptus and elephant grass, shown in the supplementary information SI.1, is assumed to remain constant over time.

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[10] Sugarcane is cultivated in a cultivation period of 6 years. As yield decrease over time (roughly 20% compared to the previous harvest (Isaias de Carvalho Macedo et al., 2004), the plantation is renewed after 6 years.

[11] (Isaias de Carvalho Macedo et al., 2004) found that an average yield of 68.7 TC/ha-year corresponds to 106, 90, 78, 71 and 67 TC/ha for the five consecutive harvests in a ratoon.

[12] The state of Sao Paulo has approved a law in 2002 to gradual eliminate pre-harvest burning of sugarcane field by 2021 in mechanized areas and by 2031 by non-mechanized areas (Luz et al., 2012)

Table 4-2 Technical parameters for biomass cultivation; yield and annual yield increase, and sugar- and fibre content of first generation biomass feedstock.

Item	**2010 value (common range)**	**Unit**[K]	**Annual change**[L]	**2030 value (based on 2010 value and annual change)**
Yield SC[A]	85 (80-92)	TC/ha	0.9%	100
Yield EC[B]	85 (80-92)	TC/ha	2.0%	126
Yield SS[C]	50 (49-63)	TC/ha	2.0%	65
Yield EU[D]	47 (27-53)	m^3/ha-year	3.0%	70
Yield EG[E]	30 (29-36)	dry tonne/ha-year	1.6%	45
Sucrose content sugarcane[F]	14.5 (14.0-15.0)	%	0.5%	16.6
Sucrose content energycane[G]	14.5 (14.0-15.0)	%	-1.0%	12.0
Sucrose content sweet sorghum[H]	12.0 (10.9-15.5)	%	1.0%	12.6
Fiber content SC[I]	14.0 (11.0-16.0)	%	-1.0%	12.4
Fiber content EC[G]	14.0 (11.0-16.0)	%	2.0%	17.0
Fiber content SS[J]	14.0 (13.9-14.5)	%	0%	14.0

[A] Current achieved yield in São Paulo state is around 80-85 tonne cane/ha-year(Macedo et al., 2008), historically, the yield trend has been fairly linear (MAPA, 2010), extrapolating this trend, this would lead to a yield of 102 TC/ha-year in 2030, in line with future yield expectations of (Leal et al., 2012). The yield range (between brackets) is the averaged yield found in the traditional sugarcane cultivation regions (Centre-South region of Brazil), as reported by (XAVIER et al., 2010)

[B] Energycane is seen as high yielding fibrous sugarcane, therefore current yield is assumed to be similar to sugarcane, while the annual increase is higher reaching 126 TC/ha-year, similar to the energycane yield expectations of (Leal et al., 2012)

[C] Current yield are around 50-60 tonne wet sweet sorghum/rotation period (100-120 days), an yield increase of 2% would support the yield expectations of (Agroenergia, 2011). Yield ranges found are between 54 and 69 short ton (Almodares & Hadi, 2009)

[D] Eucalyptus yields of 47 m^3/ha-year can be attained in São Paulo state, which would represent 23.5 dry tonne/ha-year. Yields of 70 m^3/ha-year are foreseen to be achievable (Stape et al., 2010). In 2009 the yield range in Brazil was between 27 and 53 m^3/ha-year, for the regions Pará and Paraná respectively (Bracelpa, 2009), similar to (Carlos Jose Caetano Bacha, 2008)

[E] Current elephant grass yields are around 30 dry tonne/ha-year (Morais, Souza, Leite, Henrique, & Soares, 2009); the yield range for research plot is between 24.5 and 34.4 dry tonne/ha-year, the yield trend is assumed to be similar to sugarcane; due to the lack of data.

[F] Common values found in literature indicate a current sugar content between 14% (Ensinas, Nebra, Lozano, & Serra, 2007) and 15.3% (Dias et al., 2012) Next to yield also the sucrose content of sugarcane is expected to increase in the future (Leal et al., 2012), an annual increase of 0.5% is assumed, in line with the expected sucrose content of sugarcane of 16.5% in 2030 by (Leal et al., 2012) and in line with the historically observed trend between 1980 and 2004 (van den Wall Bake et al., 2009)

[G] The start point for energycane is similar to sugarcane, but the annual change is selected as such that future values are in line with the future expected sugar- and fiber content as presented by (Leal et al., 2012)

[H] The current sugar content of sweet sorghum varieties designed for ethanol production are between 10.9 – 15.5% (Embrapa, n.d.-a, n.d.-b) potential increase in sugar content is assumed to be similar to sugarcane.

[I] On average the fiber content of sugarcane is around 140 kg dry/TC, or 14% (Dias, Cunha, et al., 2011), common range is 11-16% (Bonomi et al., 2011).

[J] Fiber content of sweet sorghum is around 13.9 – 14.5% (Bonomi et al., 2011), a value of 14% is selected in line with sugarcane.

[K] The yield of the different biomass types does not compare easily due to differences in moisture content. We provided the data is most commonly used units, despite that easy comparison is difficult.

[L] The annual change is specified as the annual increase or decrease of the parameter at hand. For example sugarcane yield would increase to 102 TC/ha/year

4.4.2 Technical data industrial processing

4.4.2.1. First generation technology

For first generation technology the sugar extraction efficiency and extraction losses are considered, together with the fermentation and distillation efficiency, leading to the industrial ethanol yield. For those parameters the 2010 value is considered based on literature, and for the future outlook updated with the expected annual change, until it reaches the maximum or minimum value, see Table 4-3. No difference in ethanol production efficiency is considered between the basic and optimized first generation set-up, as the dominant element do not differ. The scale of first generation industrial processing in 2010 is assumed to be 500 TC/hour, a relatively large scale autonomous distillery (Dias, Cunha, et al., 2011). The electricity consumption for the basic and optimized process are 28 kWh/TC input and 46 kWh/TC input (Dias, Cunha, et al., 2011; Júnior et al., 2009). The steam demand is set to 500 kg steam/TC for the basic configuration, based on the values found in (Ensinas et al., 2007; Pellegrini & de Oliveira Junior, 2011). For the optimized configuration a steam reduction of 75 kg steam/ TC, compared to the basic configuration, is considered due to the use of molecular sieves (Dias, Cunha, et al., 2011).

Table 4-3 Technical parameters first generation ethanol production technology

Item	**2010 Value**	**Annual change**[F]	**Maximum / minimal value**
Extraction efficiency[A]	96%	1%	100%[G]
Extraction losses[B]	0.5%	0%	0.2%
Fermentation efficiency[C]	90%	1%	94.5%[D]
Distillation efficiency[E]	99%	0.1%	100%[G]

[A] Historically the extraction yield improved from 92% 97.5% for the best available technology, common average extraction efficiency 96% (Walter, 2008)
[B] Extraction losses were reduced from 2% to 0.2% for the best available technology (Walter, 2008). For extraction losses
[C] Fermentation efficiency improved from 83% to 91.2% nowadays by better yeast selection, microbiological and process control. Also the production time decreased, ethanol percentage in broth increased and large-scale continuous fermenters were developed. Best available technology fermentation steps reach efficiencies of 93% (Walter, 2008).
[D] Given the chemical equations, the stoichiometric conversion of 1 kg sugars is 0.511 kg ethanol and 0.489 kg CO_2 (Carioca & Leal, 2011). Given the coproduction of glycerol, organic acids and yeast the maximal potential yield is 0.483 kg ethanol per kg of sugars (this represents 94.5% of the theoretical value) (Carioca & Leal, 2011).
[E] Due to improvements in process control and higher ethanol percentage ethanol distillation improved from 96% in the 1990's to 99.5% currently achieved (Walter, 2008).
[F] The annual change is specified as the increase or decrease of the parameter as hand, for example the fermentation efficiency could increase to almost 100% with this annual increase in 10 years, if there would be no maximum scale specified.
[G] For extraction efficiency and distillation efficiency no maximum value was found, therefore the maximum value is set to 100%, although debatable, no information was found on the practical limit of these efficiencies.

4.4.2.2. Second generation technology

For the ethanol production from lignocellulosic biomass feedstock the conversion efficiency from polysaccharides to monosaccharides and the conversion to ethanol is applied for the basic and optimized set-up. Based on available literature, a 2010 value, annual change and a maximum value for conversion efficiency is assumed for both types (basic and optimized). In Table 4-4 an overview of the data used for the production of second generation ethanol is given. The scale of a second generation technology is based on the size of the second generation process of an integrated first-and-second generation process. This scale is based on the processing of all available bagasse by-products of a sugarcane based first-and-second generation plant. To enable fair comparison the scale of a second generation plant with an integrated first-and-second generation process, the dry tonne input (e.g. cane bagasse or eucalyptus wood) for the second generation process is similar. The electricity consumption for the basic and optimized second generation process are 218 and 190 kWh/tonne dry input respectively (Hamelinck et al., 2005). Steam consumption, mainly caused by the pretreatment section, is set to 1400 and 2300 kg steam/tonne dry input for the basic and optimized configuration (Hamelinck et al., 2005).

Table 4-4 technical parameters second generation ethanol production technology

	Basic set-up			**Optimized set-up**		
Item	**Value**	**Annual Change**	**Maximum value**	**Value**	**Annual increase**	**Maximum value**
Glucan-glucose conversion[AD]	75%	1%	80%	91%	1%	95%
Xylan-xylose conversion[B]	60%	1%	80%	80%	1%	90%
Arabinan-arabinose conversion[C]	60%	1%	80%	80%	1%	90%
Galactan-galactose conversion[C]	60%	1%	80%	80%	1%	90%
Mannan-mannose conversion[C]	60%	1%	80%	80%	1%	90%
Glucose-ethanol conversion[E]	80%	1%	95%	90%	1%	95%
Xylose-ethanol conversion[F]	75%	1%	90%	75%	1%	90%
Arabinose-ethanol conversion[G]	0%	-%	-%	75%	1%	90%
Galactose-ethanol conversion[G]	0%	-%	-%	0%	-%	-%
Mannose-ethanol conversion[G]	0%	-%	-%	0%	-%	-%

[A] The conversion of glucan to glucose is set to 75% for the basic set-up in 2010, similar to the low end provided by (Hamelinck et al., 2005), given the trend between current and 2015 hydrolysis efficiency, as provided by (Dias et al., 2012), a maximum of 80% is assumed, well below the estimation of 91% of (Humbird et al., 2011)

[B] Conversion of xylan, galactan and mannan sugars to xylose, galactose and mannose efficiency is set to 60%, similar to (Dias et al., 2012; Humbird et al., 2011), maximum value assumed are 80, in line with maximum values of basic set-ups of (Humbird et al., 2011). For more advanced set-ups the conversion efficiencies are similar to xylan conversion (Chovau et al., 2013)

[D] Glucan to glucose conversion can be rather efficient, values found are in the range 90-98% (Chovau et al., 2013), a current value of 91% is assumed, in line with (Humbird et al., 2011) slowly increasing to 97% for future technologies (Humbird et al., 2011)

[E] The conversion of glucose to ethanol is in the range of 80% to 95% (Dias et al., 2012; Humbird et al., 2011), therefore a current value of 80% and 90% are choosen for the basic and optimized set-up,, with a maximum of 95% (Humbird et al., 2011)

[F] The range of efficiency for xylose to ethanol found is between 76% and 80-90% (Hamelinck et al., 2005; Humbird et al., 2011), both high-end values. A value of 75% is chosen as start point, with an increase to 90%.

[G] For arabinose, galactose and mannose to ethanol conversion is neglected by (Humbird et al., 2011); efficiencies have been set to 0% for the basic technology set-up. For the optimized set-up, conversion efficiency for arabinose to ethanol is assumed similar to xylan-ethanol based on (Chovau et al., 2013)

4.4.3 Economic data for industrial processing

4.4.3.1. First generation technology

To assess the total equipment costs of a first generation industrial processing plant, the installation is broken down into 6 elements, see Table 4-5. The total installation costs of a basic first generation facility, capable of processing 2 million tonne cane would be around 172 MUS$. This is in line with the investment range of 57 to 86 US$ per tonne cane input (Pedro Valenim Marques, 2008), but higher compared to the 117 MUS$ for a 2 million tonne cane processing plant as described by (Macrelli et al., 2012).

Table 4-5 technical parameters second generation ethanol production technology

Component first generation	**Base scale**	**Investment base costs [MUS$]**	**Scale factor**	**Maximum scale**	**Installation factor**
Cane reception and juice extraction[A]	500 tonne cane/h	13.18	0.6	500	1.38
Juice treatment[B]	75 t ATR/h	5.264	0.71	-	1.84
Fermentation[C]	75 t ATR/h	14.14	-	75	1.88
Distillation and dehydration[D]	44 m^3 EtOH/hour	10.69	0.68	25	1.51
CHP[E]	362 MW_{HHV}	33.00	0.75	-	1.4
Other[F]	-	1.83	-	-	-

[A] The investment costs of cane reception and juice extraction is based on the investment costs of (Dias, Cunha, et al., 2011) and the contribution of cane reception to total equipment costs, as specified by (Júnior et al., 2009) (Isaias de Carvalho Macedo, Leal, & Silva, 2004) provided information on the mills tandem sizing needed to provide 120 000 L ethanol/day, corresponding to 250000 tonne wet sugarcane/year. The installed mill tandem size is 30”x 54” for sugarcane crushing. Given the mill tandem sizing estimating, as shown by (Sugartech, 2014), the mill capacity of a 54” inch (roll diameter is assumed to be half of the roll length, roll speed 4 rpm and 14% fibre) diameter mill is about 94 TC/hour. A 102” inch roll diameter crusher, maximum size in the Sugartech equipment sizing calculator, would under the same parameter capable to process 542 TC/hour. Given an overcapacity of 25% this would be in the same range as the 500TC/hour of (Dias, Cunha, et al., 2011). Therefore, the base scale and maximum scale is set to 500 TC/hour.

[B] The juice treatment section cover about 9% of the total equipment costs of a first generation industrial processing plant (Júnior et al., 2009). Given a total equipment costs of 150 MUS$, for a 2 MTC/year processing plant (Dias, Cunha, et al., 2011), the juice treatment section would be around 5.26 MUS$. Given that the main elements in the juice treatment section are tanks and settler, no maximum scale is assumed, with a scale factor of 0.71, based on the scale factor of a overliming tank as specified in (Humbird et al., 2011). Given a sugar content of 14%, this means the juice treatment section specified by (Dias, Cunha, et al., 2011) is capable of processing 75 tonne TRS/hour. Although this unit is unconventional is does enables to scale the equipment for cane with a variety of sugar content; like the difference between sugarcane and energycane, given all other parameters remain constant.

[C] The fermentation section in total covers 25% of the total equipment costs of a first generation industrial processing plant (Júnior et al., 2009), which would represent 14.14

MUS$$_{2010}$/ 2M tonne installation (Humbird et al., 2011). Most of the scale factors have been found in (Humbird et al., 2011); this sources does not specify a scale component for fermenters. As the maximum scale is similar to the scale of the costs source, we consider no scale effect: a 2 Million tonne sugarcane per year processing plant corresponds to a flow of 75 tonne TRS/hour. Given a continuous fermentation process, with a production time of 8.5 hour (Walter, 2008), and the scale of fermentation tanks between 300 and 3000 m^3 (Basso, Basso, & Rocha, 2010), the max processing capacity is 75 tonne TRS/hour, based on a specific density of slurry of 1 kg/L and a sugar content of 22.5 wt% (Dias, da Cunha, et al., 2011).

[D] A distillation section does represents 15% of the equipment costs of a 2 Million (500TC/hour) first generation plant, resulting in 10.69 MUS$/plant (Júnior et al., 2009) (Dias, Cunha, et al., 2011). The maximum scale for distillation is assumed to be 25 m^3 ethanol/hour as specified for distillation of ethanol for second generation (Humbird et al., 2011). A scale factor of 0.68 is applied (Humbird et al., 2011). With an ethanol yield of 88 Liter ethanol/TC and a sugarcane processing capacity of 500TC/hour would yield 44 m^3/hour (Dias, Cunha, et al., 2011). For the optimized technology an increase of 10% is assumed for the use of molecular sieves (Dias, Cunha, et al., 2011)

[E] The largest share of equipment costs are spend on the cogeneration unit to convert residues (cane bagasse, cane trash or lignin-rich residues) into steam and electricity for the process and surplus electricity. (Dias, Cunha, et al., 2011) provided an investment costs of 33 MUS$$_{2009}$ for a 375 MW[13] CHP unit (Dias, Cunha, et al., 2011). No maximum size for a combined heat and power unit was found, therefore, no maximum scale is assumed. A scale factor of 0.75, similar to the scale factor of a combustion reactor (Humbird et al., 2011).The scale of the CHP unit is designed on the HHV of the residue input (18MJ/kg for bagasse). For the use of high pressure boilers a 40% increase in equipment costs is assumed, similar to (Dias, Cunha, et al., 2011)

[F] Given the percentages of the total capital investment costs of a first generation plant, as provided by (Júnior et al., 2009), an additional 6%, or 1.83 MR$ is added as additional costs.

4.4.3.2. Second generation technology

A second generation facility is broken down into 8 main elements; feed handling, pretreatment, hydrolysis and fermentation, distillation, solid separation, waste water treatment, cogeneration and others, as shown in Table 4-6. The equipment costs of the different elements in second generation processing are predominantly based on the equipment cost as specified by (Hamelinck et al., 2005; Humbird et al., 2011). According to a review performed by (Chovau et al., 2013), the total equipment cost of these publications are on the high end of the spectrum, but result in low ethanol production cost due to the high industrial conversion efficiencies.

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[13] Dias 2011 provided the LHV of bagasse as 7.565 MJ/kg (50% moisture); which corresponds to a HHV of 18 MJ/kg given a hydrogen fraction of 0.062, evaporation heat of water of 2.26 MJ/kg, and a water mass of 8.9 [kg/kg] (Blok 2007).

Table 4-6 technical parameters second generation ethanol production technology

Component Second generation	**Base scale**	**Investment base costs [MUS$]**	**Scale factor**	**Maximum scale**	**Installation factor**
Feed handling[A]	110 dry tonne/hour	6.50	0.6	110	1.81
Steam explosion[B]	83 tonne dry biomass input/hour	1.70	0.78	83	2.36
LHW[C]	83 tonne dry biomass input/hour	3.06	0.78	83	2.36
On-site enzyme production[D]	50 kg cellulase/hour	2.62	0.8	50	2.03
SSCF reactor[E]	1.04 tonne EtOH/hour	0.80	0.8	-	1.89
CBP reactor[E]	1.04 tonne EtOH/hour	0.80	0.8	-	1.89
Distillation[F]	44 m^3 EtOH/hour	35.69	0.68	25	1.51
Solids separation[G]	10.1 tonne dry solids/hour	1.30	0.65	10.1	2.2
Water treatment, including digestion[H]	400 tonne waste water/hour	1.83	0.51	-	1.04
CHP[F]	362 MW	46.00	0.75	-	1.4
Other utilities[I]		6.00	1	-	-

[A] Total equipment costs of the feed handling is 11.68 $MUS\$_{2010}$, for an installation capable of handling 110 tonne dry/hour (Humbird et al., 2011). As the main component, the shredder, reached already its maximum scale at this capacity, a maximum scale of 110 tonne dry/hour is assumed, with a scale factor of 0.6 (Humbird et al., 2011). Overall for this section an installation factor of 1.81 is assumed (Humbird et al., 2011). For first-and-second generation installation this section is eliminated, as the sugar-crop is already shredded in the first generation process.

[B] Steam explosion is currently being considered as a viable option for pretreatment. For steam explosion total equipment costs, including ion exchange and overliming, would result in an equipment costs of 5.4 MUS$ (capacity 83 tonne/hour) (Hamelinck et al., 2005).

[C] A LHW reactor would cost around 3.06 $MUS\$_{2010}$ for a 83 tonne dry biomass input/hour reactor. For both steam explosion and LHW a scale factor of 0.78 and an installation factor of 2.36 is assumed (Hamelinck et al., 2005).

[D] For the optimized technology (LHW pretreatment and on-site enzyme production) an enzyme unit is incorporated. A cellulase production unit capable of producing 50kg cellulase/hour would costs 2.62 MUS$, a scale factor of 0.8, installation factor of 2.03

(Hamelinck et al., 2005).
[E] Two main types are distinguished in this research; a SSCF reactor and a CBP reactor, but the equipment costs are similar for both, similar to (Hamelinck et al., 2005). For both reactors the equipment costs are set to 0.80 MUS$\$_{2010}$, to produce 1.04 tonne ethanol/hour, a scale factor of 0.8 and an installation factor of 1.89 (Hamelinck et al., 2005).
[F] Similar to the first generation ethanol dehydration, see Table 4-5
[G] The scale of the solids separation unit is based on the available residues; all residues not being converted to ethanol or CO$_2$. The equipment costs of 1.30 MUS$ for an unit capable of processing 10.1 dry tonne/hour (Hamelinck et al., 2005)
[H] The digestor is scaled based on the amount of waste water from the process, in line with (Hamelinck et al., 2005) this is set to 9.4 tonne waste water per tonne ethanol produced. (Hamelinck et al., 2005). Equipment costs are based on (Hamelinck et al., 2005)
[I] Similar to the cogeneration unit in first generation process, see Table 4-4

4.4.4 Sensitivity analysis

The different variables used in the sensitivity analysis are depicted in table 4-7.

Table 4-7 Sensitivity parameter input data

Parameter	Value of standard sensitivity analysis	Value of regional sensitivity analysis
Land cost	- [A]	456 / 190 / 216 US$/ha[B]
Sugarcane yield	50-120%[C]	60-115% / 40-85% / 60-120%[D]
Eucalyptus yield	50-120%[C]	65-135% / 60-110% / 60-120%[E]
Fertilizer prices	70-130%[F]	
Capital investment	70-130%[G]	
Ethanol yield	70-105%[H]	
Electricity revenues	70-160%[I]	

[A] Land cost are not varied for the general sensitivity analysis
[B] Land costs for Sao Paulo, Mato Grosso and Mato Grosse de Sul respectively, based on the variation in land cost for agricultural land historically, based on (Gasques et al., 2008)
[C] The yield variation found in sugarcane cultivation in the conventional sugarcane cultivation area and the expansion regions is between 55 and 105 TC/ha-year, therefore a yield variation of 50 to 120% is chosen (XAVIER et al., 2010). A similar yield variation is selected for eucalyptus
[D] For sugarcane yield a variation of 60-115% is considered for Sao Paulo. For Mato Grosso (40-85%) and Mato Grosso do Sul (60 to 120%) similar ranges are considered; the ranges relate to the base value of Sao Paulo (Toth, Kozlowski, Prieler, & Wiberg, 2012).
[E] For eucalyptus a yield variation compared to the base value of Sao Paulo of 65-135% (Sao Paulo), 60-110% (Mato Grosso) and 60-120% (Mato Grosso do Sul) based on the

current average yield (Bracelpa, 2009), and the variation in yield found in field plot (Stape et al., 2010).

[F] Due to the variation in fertilizer prices found, the fertilizer prices for all types of fertilizers range between 70 and 130%.

[G] For capital cost the range is set to 70 to 130%, similar to (Chovau et al., 2013)

[H] The ethanol yield for first generation is reaching practical limits and is highly robust, for second generation processing however, the ethanol yield is less certain. Given the variation in ethanol yield found by (Chovau et al., 2013) for second generation processing 290 – 385 liter ethanol/dry tonne input, a range of 70 to 105% is considered, as the ethanol yield considered in this analysis are at the high end of the spectrum and reaching theoretical limits.

[I] Electricity revenues may vary greatly; (Dias et al., 2012) valued electricity revenues up to 0,091 US$/kWh, while (Chovau et al., 2013) ranged between 0,058 and 0,078 US$/kWh. A range of 70 to 160% is considered, compared to our base value, to determine the impact of fluctuating electricity revenues.

4.5 Results

4.5.1 Current and future biomass cultivation costs

In Figure 4-3, the breakdowns of biomass cultivation costs for sugarcane, energycane, sweet sorghum, eucalyptus and elephant grass are shown, expressed in US$/tonne wet biomass and in US$/GJ$_{HHV}$ (see Appendix SI.1 for heating values of the different biomass feedstock). The total cultivation costs are broken down into several components, e.g: cost of land, machines, fertilizers, agrochemicals, seed/seedlings and other costs. The graph shows the bottom-up cultivation costs for São Paulo state. Due to the yield increase and the utilization of mechanized and ETC cane harvesting, the total cultivation costs decrease and the cost breakdown changes towards 2030. The cost of land, labour, and agrochemicals, (expressed in costs per hectare) are directly affected by yield. While cost related to the use of machinery; machine investment, operational labour, diesel, amount of seedlings used, machine maintenance and lubricants) are reduced due to the utilization of machinery. The fertilizer requirements are assumed to be directly linked to yield. Therefore, the fertilizer costs per tonne of cane remains constant over time. For energycane a similar trend is observed for the different cost elements. However, due to a stronger yield increase, the total cultivation costs are lower for energycane compared to sugarcane in 2030. As the ‘other’ cost are determined as fixed percentage of all other elements, the ‘other’ costs for energycane are lower as well.

For sweet sorghum, land costs are included in Figure 4-3, even though sweet sorghum is used as complementary crop with cane which would exclude land cost as sweet sorghum is cultivation in between sugarcane rotations. The machinery costs are mainly determined by harvesting equipment. The cost of fertilizers (labelled as N-fertilizer costs), is the main cost component of sweet sorghum cultivation, caused by the high fertilizer input requirements.

For eucalyptus cultivation cost, the land and machinery costs are the most prominent factors of the total cultivation costs, while fertilizer costs only add a minor share. The total land costs are 14.0 US$$_{2010}$/tonne wet eucalyptus in 2010, and total machine and machinery operation costs add up to 8.9 US$$_{2010}$/tonne wet eucalyptus in 2010. The total machinery operation costs (operational labour, diesel, machinery, and machinery maintenance) consists predominantly of the harvesting costs of eucalyptus.

Elephant grass has a similar costs structure as eucalyptus, but next to land costs and harvesting costs (machinery, diesel, machinery maintenance) also fertilizer costs are important elements of the total cultivation costs. Total elephant grass plantation establishment cost (not shown) are relatively high, but are spread over the total biomass production of the total lifetime of the plantation (20 years).

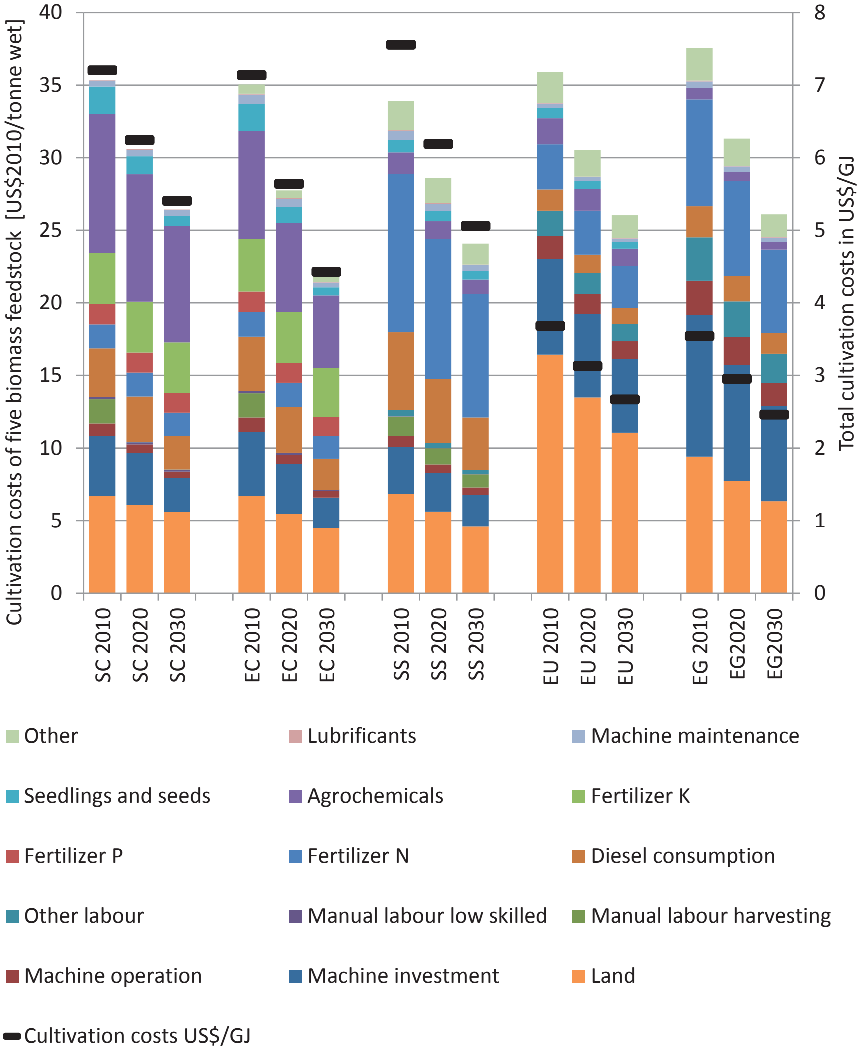

Figure 4-3 Projected biomass cultivation costs of sugarcane (SC), energycane (EC), sweet sorghum (SS), eucalyptus (EU) and elephant grass (EG) in São Paulo state, in 2010, 2020 and 2030.

4.5.2 Total ethanol production costs based on first generation technology

In first generation ethanol production, sugarcane, energycane and sweet sorghum are processed to ethanol and bagasse and cane-trash are converted to electricity. The annual amount of sweet sorghum used in the industrial processing facility is corrected for the potentially available production of sweet sorghum on cane-land between two consecutive cultivation cycles of sugar- or energycane. The Figures 4-4 and 4-5 show the improvement potential of changing from a basic to an optimized 1st generation technology, using energycane instead of sugarcane, complementing cane with sweet sorghum, and collecting and using cane-trash for (more) surplus electricity Several (theoretical) combinations of biomass feedstock and industrial processing technologies are possible, only configurations which show the impact the utilized feedstock or choice of technology are shown. In short, the configurations shown in Figures 4 and 5 are:

- Basic first generation technology using sugarcane (Basic 1G SC)
- Optimized first generation technology using sugarcane (Optimized 1G SC)
- Optimized first generation technology using sugarcane and sugarcane-trash (for a larger surplus of electricity) (Optimized 1G SCT)
- Optimized first generation technology using sugarcane, sweet sorghum and sugarcane trash (Optimized 1G SC+SST)
- Basic first generation technology using energycane (Basic 1G EC)
- Optimized first generation technology using energycane, sweet sorghum and energycane trash (Optimized 1G EC+SST)

Compared to 2010, all configuration show a decrease in total ethanol production costs towards 2030. This trend in the costs of ethanol production pathways is mainly determined by the reduced feedstock costs (as shown in Figure 4-3), the higher ethanol yield (a combination of increased sugar content and improved industrial efficiency), and the lower specific investment costs due to the economy of scale (mainly in the cogeneration section). The most important improvement option is to increase the sugar content of sugarcane; this leads to higher ethanol yield per tonne of feedstock; but also to lower investment costs as the crusher is scaled to the feedstock flow. For configurations utilizing sugarcane, the basic technology set-up is the most expensive configuration. An option to reduce the costs is to change from the basic to the optimized configuration, as the increased electricity revenues reduce overall ethanol production costs. By utilizing trash, the surplus electricity reduces the total ethanol production costs, despite the higher investment costs (of the cogeneration unit) and the costs related to the collection and transport of trash. The use of sweet sorghum leads to a minor reduction in the ethanol production costs, as the capital investment is spread over a larger ethanol output, but feedstock costs (sweet sorghum also has a lower sugar content) are higher.

For energycane, the lower sugar content leads to a reduced ethanol yield causing only a small reduction in total ethanol production costs for basic first generation technology; despite the lower biomass feedstock costs, increased industrial processing scale, and improved industrial efficiency. Over time the ethanol production costs even increase, as the benefits of low feedstock costs and increased efficiency are counteracted by the lower sugar content. The use of sweet sorghum with energycane and cane-trash with optimized first generation technology reduces the costs compared to the basic first generation technology with energycane.

The transportation costs of biomass, from field to industrial plant have a small share in total ethanol production costs. The costs of transportation are dominated by the capital costs of the truck and trailer and the diesel expenses.

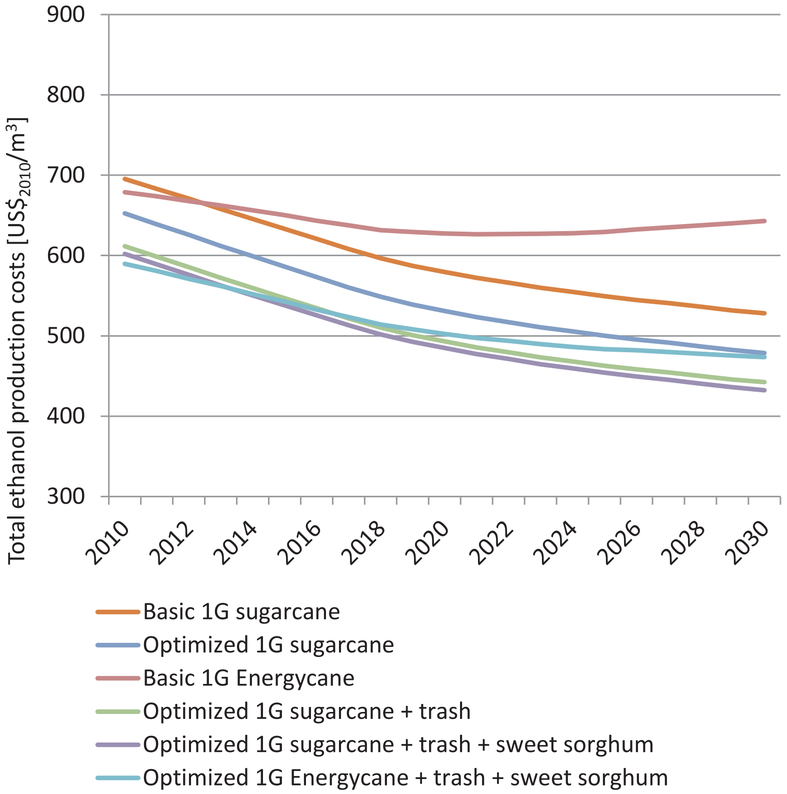

Figure 4-4 Ethanol production costs of the different first generation configurations between 2010 and 2030; using combinations of sugarcane, energycane and sweet sorghum.

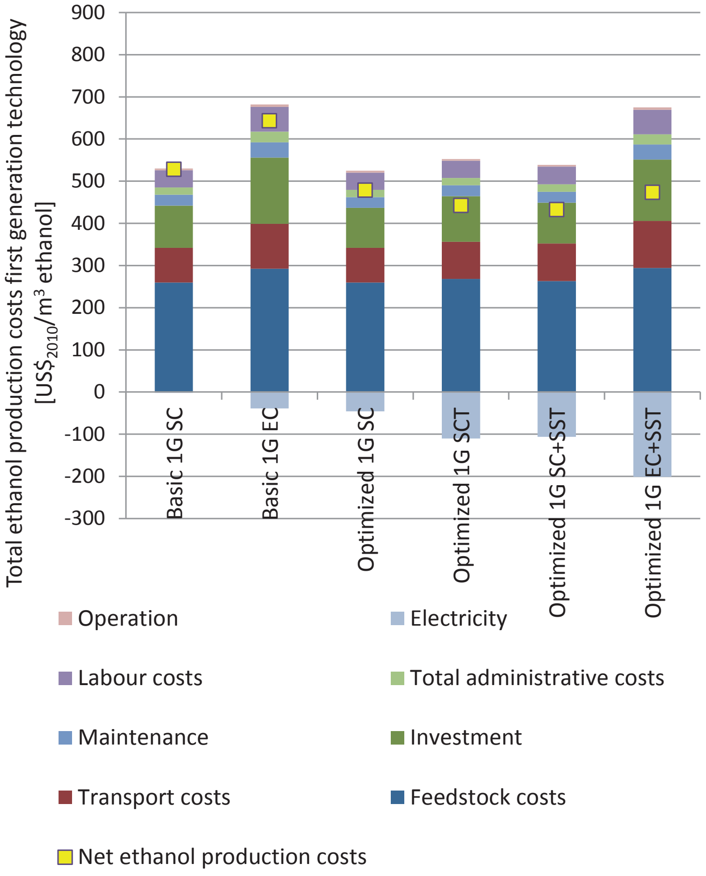

Figure 4-5 Ethanol production cost breakdown of the different first generation technologies in 2030, using combinations of sugarcane, energycane and sweet sorghum.

4.5.3 Total ethanol production costs based on second generation technology

The use of second generation technology enables ethanol production of lignocellulosic biomass like eucalyptus and elephant grass, but also sugarcane bagasse and trash. Figure 4-6 gives an overview of the trend in total ethanol production costs of second and integrated first-and-second generation processes. For second generation processing a basic and an optimized technology processing eucalyptus and elephant grass are considered. In Figure 4-7, the cost breakdowns of selected second generation and integrated first-and-second generation processes are shown.

In short, the selected configurations in Figure 4-6 and 4-7 are:

- Basic second generation technology using eucalyptus (Basic 2G EU)
- Basic second generation technology using elephant grass (Basic 2G EG)
- Optimized second generation technology using eucalyptus (Optimized 2G EU)

- Optimized second generation technology using elephant grass (Optimized 2G EG)
- Optimized 1G and basic 2G technology using sugarcane (Basic 1+2G SC)
- Optimized 1G and optimized 2G technology using sugarcane, utilizing bagasse during sugarcane harvest season (Optimized 1+2G SC)
- Optimized 1G and optimized 2G technology using sugarcane, utilizing bagasse and cane trash during sugarcane harvest season (Optimized 1+2G SCTr)
- Optimized 1G and optimized 2G technology using sugarcane and sweet sorghum, utilizing bagasse and cane trash during sugarcane harvest season (Optimized 1+2G SC+SSTr)
- Optimized 1G and optimized 2G technology using sugarcane and sweet sorghum, utilizing cane trash during harvest season, utilizing bagasse outside sugarcane harvest season (Optimized 1+2G SC+SSTr 300 days).

The reduction in total ethanol production costs of the different configurations are caused by the increased efficiency for industrial processing (both first generation and second generation), increased scale and reduced feedstock costs over time. For the optimized second generation technology utilizing eucalyptus, the reduced feedstock costs and improved industrial efficiency are the dominant factors. The economy of scale plays a minor role. Given the increase in industrial efficiency and the decrease in feedstock costs, second generation technologies have a stronger reduction in total ethanol production costs, compared to first or first-and-second generation technology.

The industrial processing costs of the basic and optimized second generation process follow a similar trend as first generation processing. The main difference between the basic and optimized second generation technology is the on-site enzyme production, which excludes the costs for cellulose for the optimized configuration. Investment costs remain the dominant factor in the total ethanol production costs of second generation industrial processing. Prominent elements in the total investment costs are the equipment costs of the cogeneration unit (38% of total equipment costs), the pretreatment (17%), and the distillation and solid separation sections (combined 18%). When commercially available the optimized second generation industrial processing is preferred over the basic second generation process, as conversion efficiencies of the optimized process are higher. Furthermore, the operational costs are reduced (no cellulose costs); the little additional investment is easily compensated by the reduced operational costs and higher ethanol output.

The integrated first-and-second generation processes use sugarcane as feedstock for ethanol production. The overall ethanol yield is mainly determined by the first generation part of the installation, and the total ethanol yield of sugarcane is superior to energycane. Therefore, the overall ethanol production costs of sugarcane are more favourable compared to energycane cellulase from an economic point of view. The ethanol yield of the first generation process mainly increases due to the sugar content of sugarcane, while in energycane the fibre content increases at the expense of the sugar content. Interesting is that the optimized second generation technology using eucalyptus follows a similar trend as the best performing integrated first-and-second generation processes, despite the difference in feedstock, conversion efficiencies, and capital investment costs.

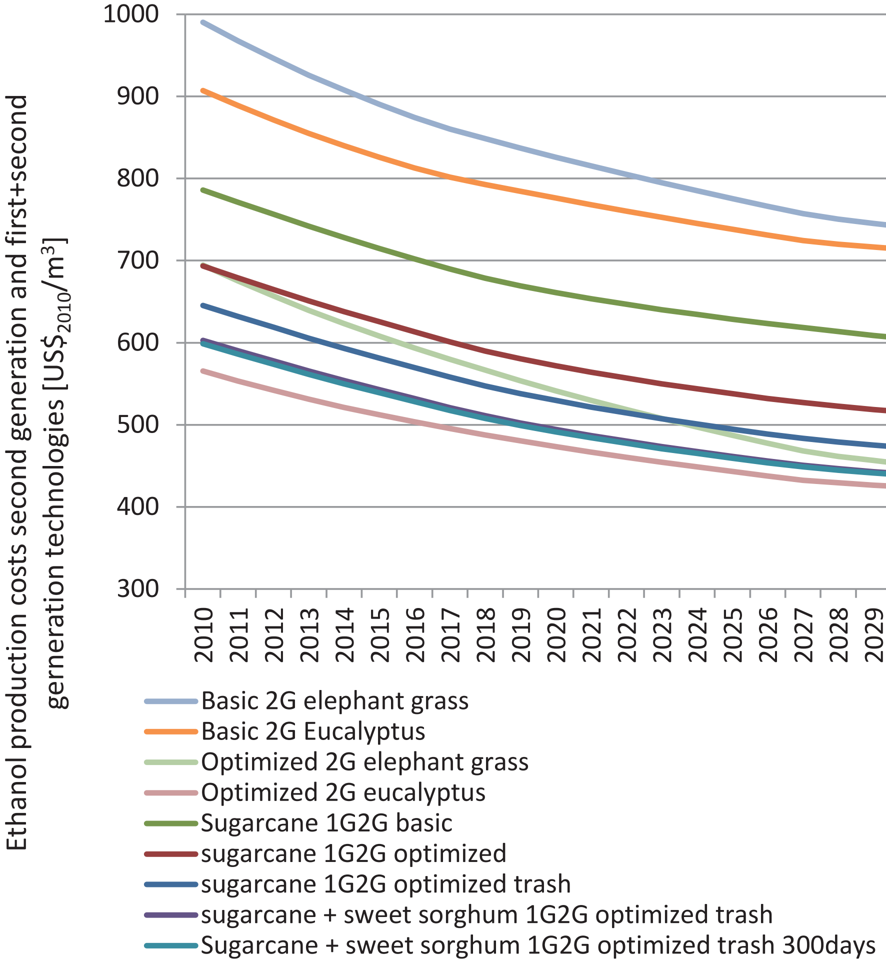

Figure 4-6 Ethanol production costs of the different second and integrated fist-and-second generation configurations between 2010 and 2030; using eucalyptus, elephant grass or combinations of sugarcane, energycane and sweet sorghum.

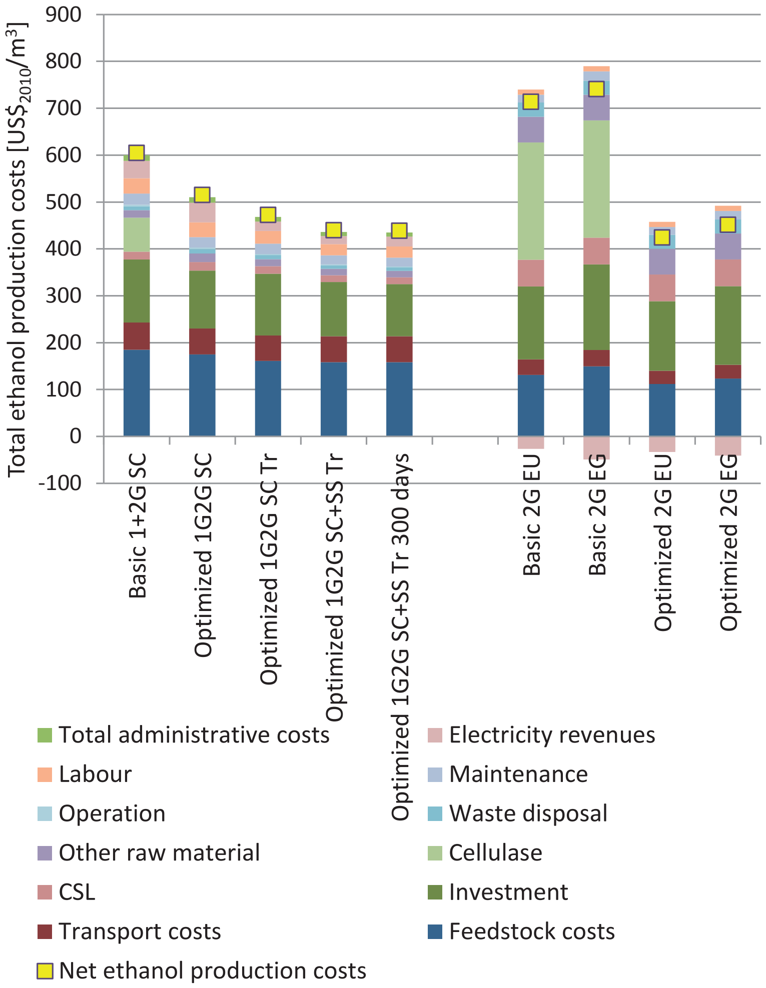

Figure 4-7 Ethanol production cost breakdowsn of the different second and integrated first-and-second generation technologies in 2030, using eucalyptus, elephant grass or combinations of sugarcane, energycane and sweet sorghum.

4.5.4 Sensitivity analysis total ethanol production

4.5.4.1. Sensitivity analysis individual parameters

In Figure 4-8, the sensitivity of the total ethanol production costs of the best performing first, second and first-and-second generation industrial processing configurations is shown. The total ethanol production costs are determined for first generation optimized process fed with sugarcane, cane trash and sweet sorghum, optimized second generation processing using eucalyptus and the use of sugarcane in optimized first-and-second generation process. For biomass yield, capital expenses, ethanol yield, electricity revenues and fertilizer prices a variation is chosen given their potential ranges, see methodology section. For the selected configurations the total ethanol production costs are most sensitive to biomass yield and ethanol yield on biomass. As seen in Figure 4-5, biomass feedstock costs are an important element in first generation processing, therefore, first generation ethanol production costs are most sensitive to yield variation. The yield variation impact especially biomass cultivation costs, but also transport costs, as transport distances increases with decreasing yield. For second generation technology a change in ethanol yield has a high impact on total ethanol production costs. A change in ethanol yield does impact most costs components (apart from the operational expenses linked to ethanol yield), including biomass feedstock costs, transport costs and capital expenses. As depicted in Figure 4-7, the total ethanol production costs of the optimized configurations are dominated by capital expenses, which could affect ethanol production costs, as seen in Figure 4-8 centre. The integrated first-and-second generation configuration is most sensitive to ethanol yield, biomass yield and capital expenses.

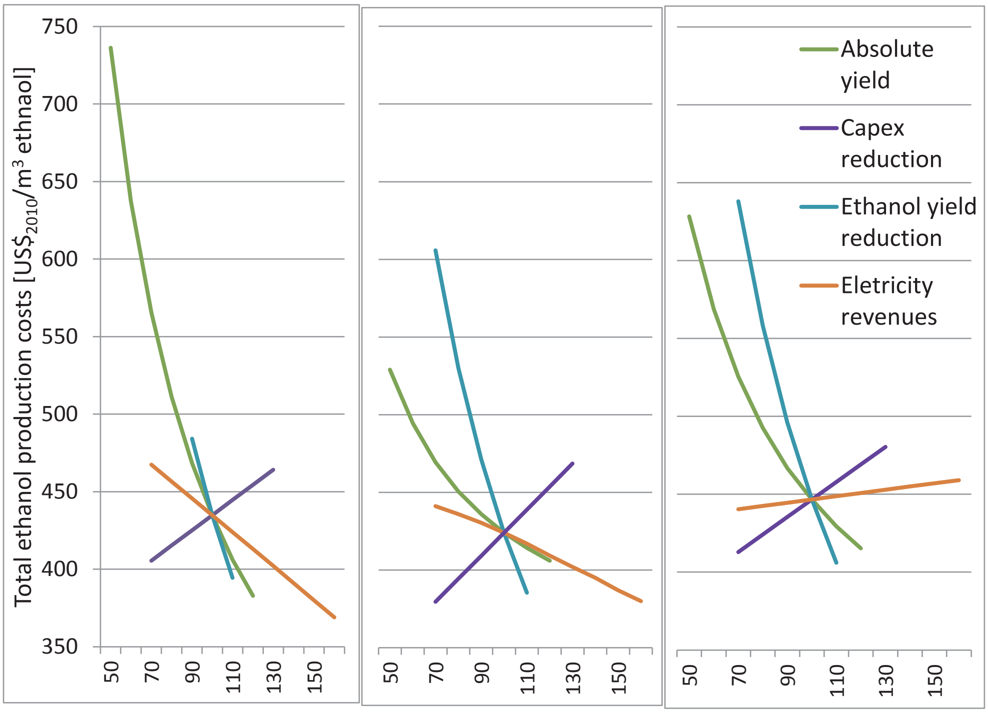

Figure 4-8 Left: Sensitivity analysis of ethanol production costs of first generation optimized technology with sugarcane, sweet sorghum and cane-trash. Centre: Sensitivity analysis of optimized second generation technology with eucalyptus. Right: Sensitivity analysis of optimized first-and-second generation technology with sugarcane, sweet sorghum and cane trash. On the x-axis the percentage change of the base figure.

4.5.4.2. Region selection for ethanol production

Taking into account the importance of yield in overall ethanol production costs as presented in Figure 4-8, and the importance of land costs in cultivation costs (see Figure 4-3), a regional sensitivity analysis is performed. For São Paulo, Mato Grosso and Mato Grosso do Sul the combined effect of regional differences in yield and land costs on the total ethanol production costs are shown in Figure 4-9. Figure 4-9 provides insight in the ranking of the different configurations given the potential yield ranges in the three selected regions. As land costs are fixed per region, the ethanol production costs, as function of yield variation, follow a similar trend per configuration. At similar yield levels the region Mato Grosso would result in the lowest ethanol production costs per technology due to the low land costs. Second generation eucalyptus ethanol production is the most attractive option and is only little affected by yield reduction. Therefore, first generation sugarcane ethanol production is only attractive at higher yield. In Figure 4-10, the yield ranges of the different technologies in the different regions are shown. For first generation processing the yield variation and the impact of yield on total ethanol production costs are much larger compared to second generation processing of eucalyptus.

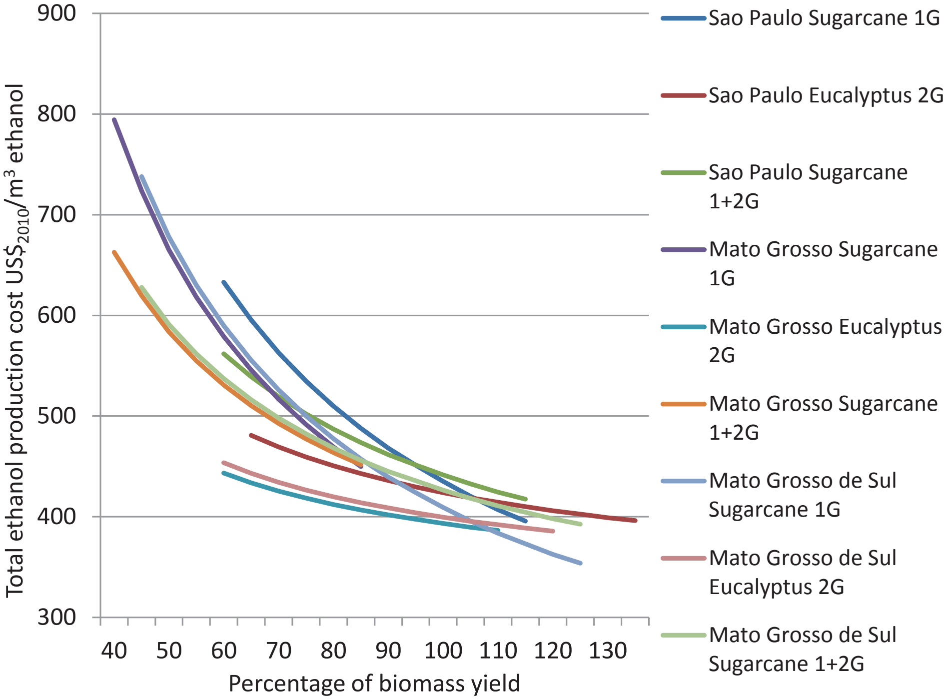

Figure 4-9 Total ethanol production costs in US$$_{2010}$/m^3 ethanol in 2030 for the three most promising configurations for the states of São Paulo, Mato Grosso and Mato Grosso do Sul given the variations in yield (as a percentage of the average yield level in São Paulo).

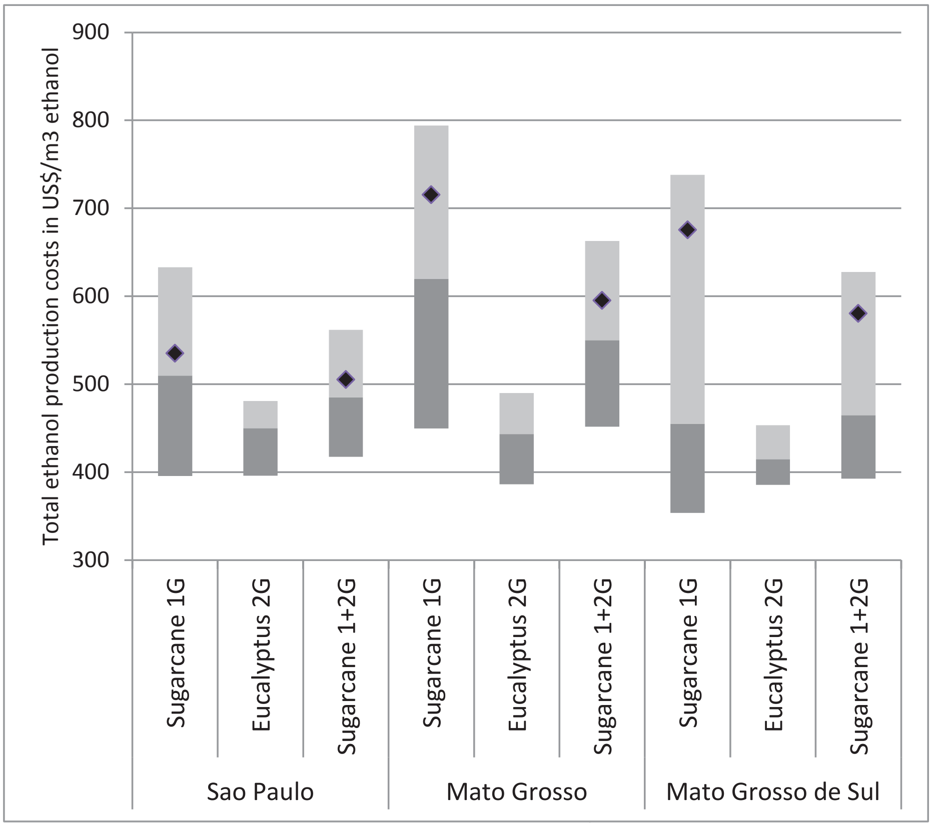

Figure 4-10 Total ethanol production costs in US$$_{2010}$/m^3 in 2030 for the different regions, given the regional variations in yield ranges and land costs. The grey boxes show the yield range of the 30% most suitable land. The range is extended to the 80% best performing suitability classes to give a larger range. The point indicates the yield levels of the largest land class in the respective regions.

4.6 Discussion and limitations of the study

4.6.1 Biomass cultivation cost

The main goal of this study was to determine detailed production cost structures of different ethanol production configurations in the state of Sao Paulo and potential expansion areas in Brazil. The development in total ethanol production costs were determined for first and second generation processing pathways between 2010 and 2030. The considered biomass feedstocks are sugarcane, energycane, sweet sorghum, eucalyptus, and elephant grass. As there is limited data available on the cultivation of energycane in Brazil, we have considered similar cultivation practices and inputs for energycane as for sugarcane. As no detailed data was found on the cultivation costs structures of eucalyptus and elephant grass in Brazil, the aggregated costs of mechanized plantation management practices of eucalyptus and elephant grass have been divided over the different elements (machine investment, operation labour, diesel, machine maintenance) with fixed factors based on sugarcane cultivation. This does not change the total cultivation cost, however, the disaggregation of total mechanized plantation management for eucalyptus and elephant grass plantations may be different.

Different elements in the cultivation costs structure are affected by biomass yield; overall, yield improvement is a prominent driver for cost reduction next to utilization of new machinery. For all five biomass crops, significant cost reductions can be achieved in the future. Yield increase is the main driver for all crops, whereas for sugarcane and energycane the utilization of novel harvest machinery may also reduce costs. The yield development is determined per biomass crop, using available literature regarding the yield outlook of these crops. Dominant elements in biomass cultivation costs are land and machinery costs (including machine investment, machine operational labour and diesel expenses). Machinery costs are mainly related to harvesting operations, especially for eucalyptus and elephant grass.

The main uncertainties of the biomass cultivation costs are the limited available data sources for a detailed cost breakdown of cultivation costs. The total cultivation costs are in line with other sources providing sugarcane cultivation costs ORPLANA, (n.d.) and XAVIER et al., (2010) and sweet sorghum cultivation costs May, Durães, Filho, Schaffert, & Parrella, (2012). No information was found on the cultivation costs of energycane in Brazil, so unfortunately our results cannot be compared to other studies. Minor information was found on the costs of cultivation practices and cultivation inputs of eucalyptus and elephant grass, but overall cultivation costs are in line wit de Wit et al., (2013) and Queno et al. (2011). The study of Crago et al. (2010) compared Brazilian sugarcane ethanol production with USA ethanol production using corn. Despite the use of different categories for the detailed cost breakdown, Crago et al., (2010) showed the importance of total machine cost, fertilizers and chemicals in total Brazilian sugarcane cultivation, while land cost play a relatively small role, compared to our results. In the publication of Crago et al., (2010) land costs are based on the leasing cost, related to the yield and potential price of total recoverable sugars in sugarcane for 2007. Corn cultivation cost in the USA are more dependent on land costs, while also fertilizers and machinery play a reasonable share (Crago et al., 2010).

4.6.2. Transportation costs

The costs of biomass transportation play a minor role in total ethanol production costs. This is in line with sugarcane transportation costs as provided by XAVIER et al., (2010). Local conditions regarding road network, land availability, distribution of land, biomass yield and scale of the industrial plant affect transportation costs of individual industrial plants. The assumed increase in capacity of the ethanol plant would require longer transportation distances. However, this is counteracted by the assumed increasing biomass yield over time. Transport distances are the main determining factor of transportation costs, which may vary per location due to the local conditions. Between the different biomass feedstock only minor differences in transport costs have been observed. Although eucalyptus has a lower moisture content compared to sugarcane, resulting in lower transport costs per dry tonne, the ethanol yield per tonne eucalyptus is lower, which would increase transportation costs if expressed per m^3 of ethanol. Overall, feedstock transportation costs per m^3 of ethanol are similar.

4.6.3. Industrial processing

The industrial processing costs, excluding feedstock and transport costs, are dominated by the capital investment costs of the industrial plant. Especially for second generation capital costs are an important share in industrial processing costs, but also in the total ethanol production costs. A higher ethanol yield would reduce depreciation of capital investment, expressed in US$ per cubic metre of ethanol. The ethanol yield of first generation processing is in line with other studies (Dias, Cunha, et al., 2011; Walter, 2008; XAVIER et al., 2010). As the ethanol yields reach their maximum operational efficiency, a further increase in ethanol yield (without an increase in sugar content) seems hardly possible. For several first generation ethanol production pathways, a considerable cost reduction can be achieved in the future. This is due to reduced feedstock costs: a combination of increases in yield and sugar content, utilization of cane-trash and sweet sorghum, increase in industrial efficiency, the use of more efficient cogeneration, and economies of scale. The dominant drivers of cost reductions are the increase in sugar content and the use of cane-trash, the latter one resulting in higher electricity revenues. As the ethanol yield of energycane is lower compared to sugarcane, energycane has higher ethanol production costs, even with lower biomass cultivation costs. In general, the most economically attractive option involving first generation technology is the use of sugarcane, sweet sorghum and cane trash in an optimized first generation industrial facility. Energycane is not an attractive option for first generation processing. Total first generation ethanol production costs are in line with other studies (e.g. (Crago et al., 2010) and (XAVIER et al., 2010), but substantial lower compared to Tao & Aden, (2009). The lower costs found by Tao and Aden are most likely a result of their more optimistic assumptions regarding feedstock costs (26 $US\$_{2005}$/tonne sugarcane), scaling factors (overall 0.6), and plant operation time (350 days/year). The Brazilian ethanol production costs in 2010 found in this study are in the lower range of the production costs of corn based ethanol in the USA, which are approximately between 460 and 860 $US\$_{2010}/m^3$ ethanol (H. Chum et al., 2011). For second generation industrial processing, large cost reductions can be achieved. The ethanol output of second generation processes are less certain as those processes are still in the research and development stage. The efficiencies for second generation processing assumed in this study, reaching 90% of its theoretical maximum in 2030, are relatively uncertain, especially for the optimized technology. If the efficiencies for second generation industrial processing do not reach the level anticipated in this research, the total ethanol production costs are heavily affected, making second generation ethanol economically less attractive. A shift from the basic process to the optimized process is potentially a major step in reducing ethanol production costs. Further reduction in ethanol production costs can be obtained by increasing the conversion efficiency and reducing biomass cultivation costs. Due to a more favourable biomass composition, eucalyptus is a preferred feedstock over elephant grass, as the ethanol yield is higher. Capital expenses remain the largest costs factor of second generation industrial processing. As industrial efficiencies have not been proven yet at large scale, ethanol production costs of second generation industrial processing are less robust compared to first generation configurations. Studies showing the ethanol production costs of second generation feedstock in Brazil were not found. An economic assessment of ligno-cellulosic feedstock in the USA showed ethanol production costs in line with the optimized configuration. Gonzalez et al., (2012) showed the ethanol production cost of eucalyptus (590 US\$/m^3 ethanol) and switchgrass (660 US\$/m^3), the later one having a higher cultivation costs and less favourable composition compared to eucalyptus in the USA. The ethanol production cost of Gonzalez et al., (2012) are lower compared to the basic second generation processing options, however, for the optimized configuration the ethanol production cost are similar for 2010. Interestingly, Gonzalez et al., (2012) showed similar cost breakdowns of second generation ethanol production compared to this analysis, namely 35% for biomass feedstock and 31% for capital depreciation.

The potential cost reduction of integrated first-and-second generation processes are based on the reduction of biomass feedstock costs, increased sugar content, increased industrial efficiency (both for the first and second generation processes) and utilization of sweet sorghum and cane trash.

The electricity revenues as specified in this study are important for first generation industrial processing configurations (Dias, Modesto, et al., 2011), and to a lesser extent for second generation industrial processing. The future prices for biomass-derived electricity are highly uncertain. The electricity surplus for first generation processing is based on the utilization of efficient boilers and consumption of trash. It is uncertain whether a 50% trash recovery is feasible and sustainable, or if an even higher recovery rate is possible. If cane trash cannot be recovered, and the electricity revenues decrease, the total ethanol production costs will increase, especially for first generation processing. The methodology to estimate the electricity surplus is a simplified approach compared to e.g. Hamelinck et al., (2005). A detailed technical modelling approach could improve the robustness of the results on the electricity surplus.

4.6.4. Overall ethanol production costs

The total ethanol production costs are expressed as potential costs of the best available technology in the year under research (between 2010 and 2030). With the increase of industrial scale, biomass yield, and industrial efficiency, the ethanol production costs decrease over time. To attain this at commercial scale, especially for second generation technologies, significant investments and research and development are necessary for the corresponding ethanol production pathways.

As the total ethanol production costs are determined by many parameters, the sensitivity analysis showed the impact of the most important parameters. The general sensitivity analysis shows the impact of biomass yield, ethanol yield, capital investment and electricity revenues. Biomass yield, especially for first generation processing, and ethanol yield, especially for second generation processing, are the most important parameters in total ethanol production costs. Potentially attainable ethanol output in the future is uncertain, especially for second generation processing, as those industrial efficiencies or sugar content have not been realized at commercial scale. The biomass yield may vary according to local conditions like soil, weather and cultivation management style. Combining the potential biomass yield and variation in land costs in Sao Paulo, Mato Grosso, and Mato Grosso do Sul provides insights in the most promising configurations in these regions until 2030. Land costs have a considerable share in biomass cultivation costs, especially for eucalyptus and elephant grass, therefore, second generation ethanol production is economically most attractive in regions with low land costs. Land costs and biomass yield may vary considerably within the regions and from region to region. Furthermore, a potential link between biomass yield and potential land costs and link between land costs and large-scale biomass cultivation are not included.

Overall, significant reductions can be achieved in ethanol production costs in Brazil. Important drivers are biomass yield, sugar content and industrial processing efficiencies; the economies of scale play a minor role. Biomass yield increase seems an evident option to reduce costs, but yield increase in terms of dry matter should not be at the expense of favourable characteristics, such as the sugar content of sugarcane, or the glucan content of lignocellulosic feedstock. Furthermore, also transportation costs can be reduced when biomass yield is increased, but this only has a marginal impact on total production costs. The anticipated increase in conversion efficiency of biomass to ethanol holds great potential for cost reduction, especially for second generation processing. First generation industrial processing is already used at commercial scale and its efficiencies are already high.

Ultimately, especially in the current Brazilian context, the pathways involving sugarcane and (optimized) first generation technology are considered likely scenarios, as the transition to optimized configurations can be done in incremental steps (both for cultivation and conversion). While a radical shift to eucalyptus and second generation on the short term seems less likely in the Brazilian context, this study shows that optimized second generation ethanol production using eucalyptus may ultimately result in competitive overall production costs. Introduction of these pathways will also depend on the success of ongoing Brazilian and worldwide RD&D efforts to further develop and commercialize second generation technologies.

The detailed ethanol production cost breakdown provides insight in the important cost elements and the potential for improvement. This can be used for biofuel support policies, research and development strategies and strategic decisions of the ethanol industry. The results indicate that in the future second generation industrial processing might have the lowest production costs. An important prerequisite is the development of commercial scale, highly efficient second generation processes. All configurations can benefit from crop improvement to improve yields while holding, or even improving sugar content. Future research should focus on crop improvement, research and utilization of improved industrial processing pathways, and detailed supply chain analysis. Furthermore, the adjoining regions of Sao Paulo state have the potential to become economically attractive ethanol production regions. The utilization of these regions would require suitable biomass varieties, and proper road infrastructure for biomass supply to the plant and the distribution of ethanol to users. Although, the total costs are important for the economic viability of ethanol production, the selection of biomass feedstocks and conversion technologies should also be based on the potential environmental and socio-economic impacts, including the impacts of land use change. Therefore, future research should focus on an integrated impact assessment of bioethanol supply chains to enable a sustainable expansion of the bioethanol sector in Brazil.

Acknowledgements

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Supportive information

4-SI.1 Composition second generation feedstock

The composition of second generation biomass feedstock used for ethanol production with first and second generation processes. Due to the lack of data the values for sugarcane bagasse and trash are also used for energycane.

Chemical component	Cane bagasse	Cane trash	Eucalyptus % dry basis	Elephant grass % dry basis (switch grass)
Glucans	41.4[A]	33.3[A]	49.5[B]	31.98[B]
Xylans	22.5[A]	18.1[A]	10.73[B]	21.09[B]
Galactans	1.3 [A]	1.5 [A]	0.76[B]	0.95[B]
Mannans	3.4 [A]	1.5 [A]	1.27[B]	0.30[B]
Arabinans	1.3 [A]	3.1 [A]	0.31[B]	2.84[B]
Lignin	23.6 [A]	36.1 [A]	27.71[B]	18.13[B]
Other (ash, acids and extractives)			9.72	24.7
HHV			19.5 GJhhv/tonne dry[B]	18.6 GJhhv/tonne dry[B]
[A] chemical analysis provided by (Chandel, da Silva, Carvalho, & Singh, 2012) [B] typical ligno-cellulosic biomass composition as presented by (Hamelinck et al., 2005)				

4-SI.2 Biomass cultivation costs elements

The total biomass cultivation cost are the sum of all cost elements in the cultivation of biomass, during the cultivation period. All operations and inputs are described in SI.6, the year of application is described in SI.7. The elements considered in total biomass cultivation costs are machine investment, diesel expenses, machine maintenance, lubricants for machinery, labour costs (4 different labour types), fertilizers costs (differentiated between N-, P- and K-fertilizer), agrochemicals, seedlings and land costs.

Machine investment cost

The total machinery investment costs, expressed as costs per ha for a specific cultivation management practices is expressed as:

$$\text{Invest} = (\text{hourly deprec. mach} \times \text{hours per ha}) + (\text{hourly deprec equip} \times \text{hours per ha})$$

Abbreviation	Description	Unit
Invest	Machine investment costs	US$/ha
Hourly deprec. mach	deprecation of machine (e.g. tractor)	US$/hour
Hourly deprec equip	Depreciation of machine equipment	US$/hour
Hours per ha	time to fulfill a certain management practice per hectare	Hours/ha

For the hourly depreciation of machine and equipment costs the Excel PMT function is utilized:

$$\text{hourly deprec} = \frac{(1 + \text{t\&g}) \times \text{PMT}(\text{disc}, \text{years}, \text{iinvest}, \text{rvalue})}{\text{workhours}}$$

Abbreviation	Description	Unit
Hourly deprec	Deprecation of capital investment divided over the annual working hours	US$/hour
t&g	percentage of additional costs for tax and garage	%
PMT	Function to determine annual depreciation for an investment	-
Disc	discount factor	12%
Years	years to discount the investment	Years
iinvest	Initial investment of a truck or trailer	US$
rvalue	residual value of the investment after time period; in this case 10% of initial investment	US$
Workhours	amount of working hours equipment is utilized per year	hours

Labour cost

For manual labour and machine operational labour the costs are expressed as labour costs by

multiplying the wage and the time to complete the management practice per hectare:

$$\text{Labour} = \text{hours per ha} \times \text{hourly wage}$$

Abbreviation	Description	Unit
Labour	Labour expenses	US$/ha
Hours per ha	time to fulfill a certain management practice per hectare	Hours/ha
Hourly wage	Wage of manual labour or operational labour	US$/hour

Diesel

The costs associated with diesel consumption of machinery is based on the hourly diesel consumption, time per hectare and the diesel price for farmers:

$$\text{Diesel expenses} = \text{hours per ha} \times \text{diesel consumption} \times \text{diesel costs}$$

Abbreviation	Description	Unit
Diesel expenses	Diesel costs per ha of a specific management practice	US$/ha
Hours per ha	time to fulfill a certain management practice per hectare	Hours/ha
Diesel consumption	diesel use of machinery per hour	L/hour
Diesel costs	diesel price	US$/L

Machine maintenance

The costs of machine maintenance are estimated based on the diesel expenses costs and the

operational labour expenses:

$$\text{Machine main} = \text{Main \%} \times (\text{Diesel} + \text{mach labour})$$

Abbreviation	Description	Unit
Machine main	Machine maintenance	US$/ha
Main %	Percentage maintenance	10%
Diesel	Diesel expenses (see above)	US$/ha
Mach labour	Operational labour machinery	US$/ha

Lubricants

Lubricants expenses are estimated based on diesel, maintenance and operational labour costs:

$$\text{Lubric} = \text{Lubric}\ \% \ \times (\text{Machine main} + \ \text{Diesel} + \text{mach labour})$$

Abbreviation	Description	Unit
Lubric	Lubricant cost	US$/ha
Lubric%	Percentage lubricants	1%
Machine main	Machine maintenance	US$/ha
Diesel	Diesel expenses (see above)	US$/ha
Mach Labour	Operational labour machinery	US$/ha

Cultivation input

For cultivation inputs; fertilizers (divided over N-, P-, and K-fertilizers), seedlings, agro-chemicals (like

limestone, plaster, herbicides and pesticides) the general formula is:

$$\text{Cult input} = \sum \text{Input use} \ \times \text{costs of input}$$

Abbreviation	Description	Unit
Cult input	Cultivation input	US$/ha
Input use	Consumption of input per ha	Tonne or m^3 per ha
Costs of input	Price of input	US$/tonne or m^3

Land costs

$$\text{Land costs} = \text{land remuneration}$$

Abbreviation	Description	Unit
Land costs	Annualized land cost	US$/ha-year
Land remuneration	Annual land cost in a certain region	US$/ha-year

Administrative costs of cultivation

The administrative costs are taken as percentage of total biomass cultivation costs. The 6% for administrative costs are considered for all crops, but based on the administrative costs for sugarcane cultivation (Pedro Valenim Marques, 2008)

$$\text{Administrative costs} = \frac{(\text{SUM}(\text{all cultivation expenses}))}{(1 - \%\text{admin})} \times (\text{SUM}(\text{all cultivation expenses}))$$

Abbreviation	Description	Unit
Administrative costs	Administrative costs	US$/tonne biomass

All cultivation expenses	Expenses of all cultivation expenses, expressed per tonne of harvest product	US$/tonne biomass
%admin	Percentage administrative expenses of total cost	6%

4-SI.3 Transport costs of biomass

Transport distance

To determine the transport costs of biomass, first the road distance between field and industrial processing plant is established:

$$\mathrm{Distance} = \sqrt{\frac{\frac{\mathrm{Capacity} \times 24 \times \mathrm{days\ of\ operation}}{\mathrm{Yield_Y}}}{\pi}} \times \mathrm{factor}$$

Abbreviation	**Description**	**Unit**
Distance	Road distance, single trip from field to industrial plant	Km
Capacity	Processing capacity industrial plant	Tonne input/hour
24	Hours per day	Hours/day
Days of operation	Annual operational time of industrial plant (harvest window)	170 days/year for 1G or 300 days/year for 2G
Yield	Annualized yield	Tonne/ha-year
Factor	Accessibility factor, to account for road network distribution, non-optimal land use, etc.	Km/ha

Number of truck trips

Based on the transportation distance, loading and unloading time and harvesting windows the number of trips per season can be determined:

$$\mathrm{Time} = \frac{\mathrm{distance}}{\mathrm{Speedf}} + \frac{\mathrm{distance}}{\mathrm{Speede}} + \mathrm{loading} + \mathrm{unloading}$$

Abbreviation	**Description**	**Unit**
Time	Time for 1 average trip	Hour
Distance	Road distance	Km
Speedf	Truck speed full	Km/hour
Speede	Truck speed empty	Km/hour
Loading	Time for truck loading	Hour
Unloading	Time for truck unloading	hour

$$\#\text{trips} = \left(\frac{\frac{\text{working hours}}{\text{day}}}{\text{time}}\right) \times \text{harvesting window}$$

Abbreviation	**Description**	**Unit**
#trips	Number of trips per harvest season	#
Working hours/day	Working hours of truck driving per day	h/day
time	Time for 1 average trip	Hours
Harvesting window	Harvesting window of biomass feedstock	Days

Truck investment cost

Similar to the cultivation equipment investment cost, for truck investment the deprecation is determined using a PMT function.

$$\text{depreciation} = \frac{(1 + \text{t\&g}) \times \text{PMT}(\text{disc}, \text{years}, \text{iinvest rvalue})}{\text{loading} \times \#\text{trips}}$$

Abbreviation	**Description**	**Unit**
Depreciation	Deprecation of capital investment divided over the annual working hours	US$/tonne biomass
T&g	percentage of additional costs for tax and garage	%
PMT	Function to determine annual depreciation for an investment	-
disc	discount factor	12%
Years	years to discount the investment	Years
Iinvest	Initial investment of a truck or trailer	US$
rvalue	residual value of the investment after time period; in this case 10% of initial investment	US$
Loading	Truck loading	Tonne
#trips	Number of trips per harvest season	#

Labour cost

Operational labour expenses are determined via:

$$\text{Labour} = \frac{\text{time } \times \text{hourly wage}}{\text{loading}}$$

Abbreviation	**Description**	**Unit**
Labour	Labour expenses	US$/tonne
time	Time for 1 average trip	Hours
Hourly wage	Wage of truck driver	US$/hour
Loading	Truck loading	Tonne

Diesel costs

The diesel cost for diesel consumption are determined via:

$$\text{Diesel} = \frac{\frac{\text{distance } \times 2}{\text{Diesel consum}} \times \text{dieselcosts}}{\text{loading}}$$

Abbreviation	**Description**	**Unit**
Diesel	Diesel expenses	US$/tonne
Distance	Road distance	Km
Diesel consum	Diesel consumption of a truck	L/km
dieselcosts	Diesel price	US$/Liter
Loading	Truck loading	Tonne

Tires

The annual expenses for tires are divided over the annual delivered loads:

$$\text{Tires} = \frac{\text{annual tires expenses}}{\text{\#trips } \times \text{loading}}$$

Abbreviation	**Description**	**Unit**
Tires	Costs for tires replacement	US$/tonne
Annual tires	Annual tires expenses	US$
#trips	Number of trips per harvest season	#
Loading	Truck loading	Tonne

Truck maintenance

The cost for truck maintenance is determined by:

$$\text{Maintenance} = \%\text{main} \times (\text{labour} + \text{diesel})$$

Abbreviation	Description	Unit
Maintenance	Costs for truck maintenance	US$/tonne
%main	Percentage to determine maintenance costs	%
Labour	Labour costs, see above	US$/tonne
diesel	Diesel costs, see above	US$/tonne

Lubricants

The costs for lubricants is determined by:

$$\text{Lubricants} = \%\text{lubri} \times (\text{labour} + \text{diesel} + \text{Maintenance})$$

Abbreviation	Description	Unit
Lubricants	Costs for lubricants	US$/tonne
%lubri	Percentage to determine lubricants costs	%
Maintenance	Costs for truck maintenance	US$/tonne
Labour	Labour costs, see above	US$/tonne
diesel	Diesel costs, see above	US$/tonne

4-SI.4 Industrial processing cost

Investment costs

The equipment cost of the individual components are scaled according to the formula below (Blok, 2007):

$$\text{EquipmentCost} = \text{Base equipment cost} \times \left(\frac{\text{Scale of equipment}}{\text{Base scale}}\right)^{\text{Scale factor}}$$

Abbreviation	Description	Unit
EquipmentCost	Equipment costs of the equipment installed	US$
Base equipment cost	Equipment costs of the base scale	US$
Scale of equipment	Scale of equipment installed	Divers units; e.g. tonne/hour
Base scale	Base scale	Divers units; e.g. tonne/hour
Scale factor	Scaling factor of installed equipment (until it reaches maximum scale)	[-]

The total investment of an installation, is the equipment costs, installation factor and additional costs for engineering and buildings:

$$\text{Total investment} = \sum\big((\text{EquipmentCosts} \times \text{factorinstal}) + (\text{EquipmentCosts} \times \text{added costs})\big)$$

Abbreviation	**Description**	**Unit**
Total investment	Total investment cost of the installation	
EquipmentCost	Equipment costs of the equipment installed	US$
Factorinstal	Factor to account for installation costs	[-]
Added cost	Factor to account for engineering, building, etc.	[-]

For first generation processing the added costs are estimated to be 30%, similar to (Dias, Cunha, et al., 2011); for second generation processing those costs are set to 57%, found in (Humbird et al., 2011).

Operational expenses
First generation:

For operational expenses we distinguish several operational expenses. The data is taken from (Pedro Valenim Marques, 2008) PECEGE 2008.

Element	**Value**	**Unit**
Sugar extraction[A]	0.022	$\text{US\$}_{2010}$/tonne input
Juice treatment[B]	0.136	$\text{US\$}_{2010}$/tonne input
Fermentation[C]	0.278	$\text{US\$}_{2010}$/tonne input
Distillation[D]	0.052	$\text{US\$}_{2010}$/tonne input
Water treatment[E]	0.055	$\text{US\$}_{2010}$/tonne input
Steam handling[F]	0.028	$\text{US\$}_{2010}$/tonne input
Fuels and lubricants[G]	0.103	$\text{US\$}_{2010}$/tonne input
Other (mainly electrodes)[H]	0.031	$\text{US\$}_{2010}$/tonne input
Maintenance (services)[I]	0.99	$\text{US\$}_{2010}$/tonne input
Maintenance (materials)[I]	1.49	$\text{US\$}_{2010}$/tonne input
Administrative industrial processing costs[J]	0.32	$\text{US\$}_{2010}$/tonne input
Total labour costs[K]	4.00	$\text{US\$}_{2010}$/tonne input
Administrative (inputs)[L]	1.20	$\text{US\$}_{2010}$/tonne input
Administrative (divers)[M]	1.8	$\text{US\$}_{2010}$/tonne input
Electricity revenues[N]	57	US\$/MWh

[A] The operational expenses for sugar-juice extraction is dominantly for knives and shredders

[B] Juice treatment is mainly the use of chemicals

[C] For fermentation different chemicals are used, but dominantly antibiotics are used to avoid other yeast strains than the preferred strain.

[D] For distillation of ethanol broth chemicals are used for dehydrating and pH control

[E] Chemical consumption for water treatment

[F] Chemical consumption to steam handling

[G] Fuels and lubricants for operating the whole installation

[H] The use of electrodes (steel) used to put in new knives in the extraction section

[I] maintenance costs are independent of scale and in total 4R\$/tonne input, maintenance costs are spread over services 60% and materials 40%.

[J] The administrative costs for the industrial plant is about 0,53 R$2008/tonne input

[K] Total labour costs are a combination of operational labour and labour expenses of the total administrative costs of an industrial processing plant

[L] Administrative inputs are the input costs for an industrial processing plant

[M] All other costs for the administrative costs of an industrial processing plant are combined in divers administrative plant.

[N] Personal communication with Arnaldo Walter, CTBE

Second generation processes

The operational expenses of a second generation plant are expressed as US$/m^3 ethanol, similar to (Humbird et al., 2011).

Element	**Value**	**Unit**
CSL[A]	57	US$/m^3 ethanol
Cellulase[B]	250	US$/m^3 ethanol
Other raw material[C]	55	US$/m^3 ethanol
Waste disposal[D]	30	US$/m^3 ethanol
Labour expenses[E]	11	US$/m^3 ethanol
Maintenance[F]	3	%
Electricity revenues[G]	57	US$/MWh

[A] The expenses for corn steep liquor, as expressed by (Humbird et al., 2011) as 20 UScents$_{2007}$/gallon.

[B] Cellulase are a dominant cost element; Of the configurations of (Macrelli et al., 2012) the cellulose expenses are between 280 and 420 US$/m^3, while (Humbird et al., 2011) expressed the costs as 184 to 260 US$/m^3. An costs of 250US$/m^3 is assumed.

[C] Expenses for other raw material is set to 5.1 to 35.9 UScents$_{2007}$/gallon, an average of 20 cents/gallon is selected for raw material costs (Humbird et al., 2011)

[D] expenses for waste disposal are between 7.7 and 58 UScents$_{2007}$/gallon, an average of 11 cents/gallon is selected for raw material costs (Humbird et al., 2011)

[E] Within (Humbird et al., 2011) a reference is made to (Aden et al., 2002) for labour expenses. (Aden et al., 2002) specified the labour costs of a 100 tonne dry/hour industrial processing unit as 2150 000 US$$_{2000}$/year.

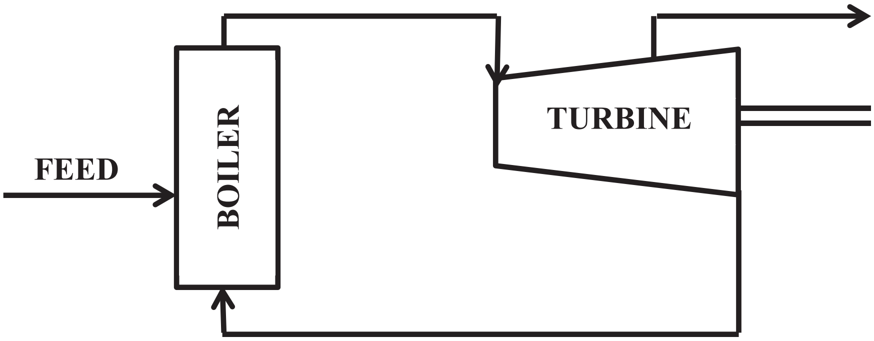
[F] For maintenance a 3% (as ratio of total equipment costs) is considered, similar to (Hamelinck et al., 2005)

[G] Personal communication with Arnaldo Walter, CTBE

4-SI.5 Steam and electricity production

Electricity and steam yield

The steam and electricity provided the cogeneration unit is used in the first generation process for electrical drivers and distillation. The boiler would be fed by residues and would generate steam, which is supplied to a steam turbine. For distillation the steam is taken from the turbine at a "tap-point".



The steam is used to generate electricity, partly used in the installation, the rest can be supplied to the electricity grid.

Electricity surplus:

$$\frac{\mathrm{E}_{\text{after boiler}} - \mathrm{E}_{\text{steam consumption}} - \mathrm{E}_{\text{after turbine}}}{3.6} - \text{electricity use} = \text{electricity surplus}$$

Item	Description	Unit
$\mathrm{E}_{\text{after boiler}}$	Energy flow after boiler, to feed turbine	MJ
$\mathrm{E}_{\text{steam consumption}}$	Energy flow for process steam	MJ
$\mathrm{E}_{\text{after turbine}}$	Energy flow after turbine	MJ
Electricity use	Own electricity use	kWh
Electricity surplus	Electricity surplus for grid supply	kWh
3.6	Conversion MJ/kWh	MJ/kWh

Energy embedded in steam after boiler:

$$\mathrm{E_{after\ boiler}} = \frac{\text{Residue flow } \times \text{HHV} \times \text{ Ƞboiler}}{\Delta\text{H Boiler}} \times \text{steam } \Delta\text{H}$$

Item	Description	Unit
Residue flow	Flow of available residues (boiler feed)	kg/year
HHV	Heating value residues	MJ/kg
Ƞboiler	Efficiency boiler	%
ΔH boiler	Heat content change in boiler (difference feed water and steam leaving boiler)	MJ/kg steam
Steam ΔH	Heat content steam after boiler	MJ/kg steam

Energy embedded in steam consumption:

$$\text{E steam consumption} = (\text{steam consumption} \times \text{input}) \times \Delta\text{H tap}$$

Item	Description	Unit
$E_{steam\ consumption}$	Energy flow for process steam	MJ
Steam consumption	Steam consumption of the industrial process	Kg steam/tonne input
Input	Annual input industrial processing plant	Tonne/year
ΔH tap 1	Enthalpy of steam at steam tap point	MJ/kg steam

Energy embedded in steam leaving turbine:

$$\left(\left(\frac{\text{residue flow } \times \text{HHV} \times \text{ ήboiler}}{\Delta\text{H Boiler}}\right) - (\text{steam consumption} \times \text{input})\right) \times \text{Hturbine} = \mathrm{E_{leaving\ turbine}}$$

Residue flow	Flow of available residues (boiler feed)	kg/year
HHV	Heating value residues	MJ/kg
Ƞboiler	Efficiency boiler	%
ΔH boiler	Heat content change in boiler (difference feed water and steam leaving boiler)	MJ/kg steam
Steam consumption	Steam consumption of the industrial process	Kg steam/tonne input
Input	Annual input industrial processing plant	Tonne/year
H turbine	Enthalpy of steam leaving turbine	MJ/kg steam

Energy embedded in steam, based on (SpiraxSarco, 2014)

	Energy embedded	**Temperature**	**Pressure**
Delta energy boiler low pressure[A]	2 MJ/kg steam		22 bar[B]
Delta energy boiler high pressure[A]	2.5 MJ/kg steam		90 bar[C]
Energy embedded in steam after boiler low pressure	3.3 MJ/kg steam[D]	300°C	22 bar
Energy embedded in steam after boiler high presuure	4 MJ/kg steam[D]	550°C	90 bar
Average energy embedded in tap point steam for process[E]	3.1 MJ/kg steam	150-200°C	2.5-6 bar
Energy embedded after turbine[F]	2.5 MJ/kg steam	100°C	0.5 bar

[A] The delta energy is the difference between boiler feed water and the energy embedded in steam flow out of the boiler

[B] For low pressure a 22 bar boiler is considered, similar to (Dias, Cunha, et al., 2011)

[C] A high pressure boiler of 90 bar is considered, similar to (Dias, Cunha, et al., 2011)

[D] The energy embedded is chosen as specific enthalpy of superheated steam of corresponding pressure and temperature.

[E] Averaged energy embedded in steam required for the first or second generation process

[F] Low pressure steam leaving turbine, before condenser and pump to become boiler feed water again.

4-SI.6 Database of costs of the different cultivation management practices.

Nm			Operation time	Machine costs	Equipment	Wage #1	Wage #2	Wage #3	Wage other	Diesel	Labour manual	Amount	Price of other
1			hours /ha	US$/ hour	US$/ hour	US$/hour				L/hour	h/ha	Kg/ha	US$/kg
2	ma	Desiccation old stumps	0.11	5.93	-	4.13				6.00			1.14
3	ma	Eliminator ratoon	1.43	8.76	0.90	4.13				15.00			1.14
4	ma	liming	1.98	10.29	1.82	4.13				8.00			1.14
5	ma	plastering	1.98	10.29	1.82	4.13				8.00			1.14
6	ma	Construction of carriers	1.81	9.56	1.43	4.13				12.00			1.14
7	ma	Maintenance of roads	0.04	19.19	-	4.13				10.00			1.14
8	ma	terracing	0.56	9.56	2.12	4.13				15.00			1.14
9	ma	disc harrow	0.41	24.38	5.73	4.13				33.00			1.14
10	ma	subsoiling	1.43	16.38	0.90	4.13				26.00			1.14
11	ma	leveling disk harrow	0.42	8.76	1.57	4.13				15.00			1.14
12	ma	Opening of furrows	3.17	10.98	0.79	4.13				14.00			1.14
13	ma	Application of filter cake	2.38	11.30	19.22	4.13				9.00			1.14
14	ma	Mating operation	1.67	6.91	0.99	4.13				12.00			1.14
15	ma	Mechanized	1.85	16.6	26.3	4.13				16.00			1.14

		planting		8	8								
16	ma	Application of Herbicide	0.11	6.12	11.49	4.13				6.00			1.14
17	ma	Operation break tenderloin (flatness)	2.08	5.38	1.18	4.13				10.00			1.14
18	ma	Fertilization of ratoon (triple operation)	2.08	8.76	1.18	4.13				12.00			1.14
19	ma	Windrowing the straw	0.22	5.47	0.51	4.13				12.00			1.14
20	ma	Charging with loader - Manual harvesting	3.88	11.75	-	4.13				7.00			1.14
21	ma	Transshipment - Manual harvesting	7.75	7.06	11.94	4.13				11.00			1.14
22	ma	mechanized harvesting	3.11	53.91	-	4.13				42.00			1.14
23	ma	Transshipment - Mechanized harvesting	7.46	7.81	12.94	4.13				11.00			1.14
24	ma	Mechanized harvesting seedlings	3.11	53.91	-	4.13				32.00			1.14
25	ma	Application of ash	1.98	10.29	1.82	4.13				14.00			1.14
26	ma	Planting with ETC	0.4	82.10	-	4.13				44.00			1.14
27	ma	Subsoiling with ETC	1.07	82.10	-	4.13				38.00			1.14
28	ma	Harvest with ETC	1.03	74.00	-	4.13				47.00			1.14
29	ma	Transshipment - ETC	3.62	8.05	13.25	4.13				21.00			1.14

30	ma	Fertilizer application with self-propelled sprayer	0.12	-	-	4.13				19.00			1.14
31	ma	Baling straw	1.3	12.14	18.23	4.13				21.00			1.14
32	ma	Loading bales (straw)	1.38	13.47	-	4.13				14.00			1.14
33	ml	Systematization area							18.15		1.10		
34	ml	Analysis of soil							21.02		0.05		
35	ml	Labor - manual planting						2.63			94.40		
36	ml	Fiscal planting						0.00	5.25		0.24		
37	ml	Monitoring Agricultural Pests						2.63			4.00		
38	ml	Pre-analysis of sugarcane						0.00	3.94		0.08		
39	ml	Carp manual transfer						2.63			21.60		
40	ml	firebreak						2.63			2.40		
41	ml	manual harvesting					3.65				79.58		
42	ml	Manual harvesting of seedlings					3.65				79.58		
43	o	Seedlings - Planting Manual										12000	0.037
44	o	Seedlings - Planting mechanized convencioanal										20000	0.037
45	o	Seedlings -										5000	0.037

		Planting mechanized with ETC											
46	ac	limestone										2000	0.0285
47	ac	plaster										1000	0.0399
48	ac	Filter cake										5000	0.000855
49	ac	vinasse										110	3.42
50	ac	ashes										5000	0
51	ac	herbicides										2.2	15.87
52	ac	Pesticides										0.16	20.18
53	ac	other defensives										0.1	394.22
54	nf	n-fertilizer at planting										30	1.30
55	pf	p-fertilizer at planting										130	1.96
56	kf	k-fertilizer at planting										120	1.78
57	nf	n-fertilizer ratoon										100	1.30
58	pf	p-fertilizer ratoon										25	1.96
59	kf	k-fertilizer ratoon										120	1.78
60	ac	maturator										0.5	50.47
61	l	land										1	456.00
62													
63	ma	Liming sorgo	0.41	7.33	3.75	4.13				13.32			1.14
64	ma	Disc harrow sorgo	0.41	11.2 1	3.75	4.13				16.27			1.14

65	ma	Leveling disk harrow sorgo	0.42	6.11	0.82	4.13				13.32			1.14
66	ma	Planting sorghum sorgo	0.54	3.38	5.42	4.13				6.50			1.14
67	ma	Fertilization surface sorgo	0.55	10.04	2.22	4.13				11.36			1.14
68	ma	Herbicide application sorgo	0.11	6.76	9.16	4.13				8.88			1.14
69	ma	Insecticide application sorgo	0.11	6.76	9.16	4.13				8.88			1.14
70	ma	Sorghum crop sorgo	2.43	30.67	-	4.13				20.34			1.14
71	ma	Overflow for sorghum crop sorgo	4.04	5.92	8.19	4.13				10.23			1.14
72	ma	Fungicide application sorgo	0.11	5.97	6.78	4.13				8.88			1.14
73													
74													
75													
76	ml	Systematization area sorgo							18.15		1.1		
77	ml	Analysis of soil sorgo							21.02		0.05		
78	ml	Fiscal planting sorgo						5.25			0.24		
79	ml	Monitoring Agricultural Pests sorgo					2.63				4		
80	ml	Carp manual transfer sorgo					2.63				21.6		

81													
82													
83	o	Sorghum seeds										4	10.58
84	ac	Insecticide - sorghum										1.2	9.52
85	ac	Herbicide - sorghum										2	4.34
86	nf	Planting fertilizer - sorghum										450	0.67
87	nf	Fertilizer coverage - sorghum										400.00	0.61
88	ac	Fungicide - Sorghum										0.75	4.88
89	ac	Insecticide seed treatment - sorghum										0.1	96.33
90	ac	Limestone - Sorghum										1000	0.040
91													
92	l	Land Sorghum										1	456
93													
94													
95	ma	Road construction											
96	ma	road maintenance											
97	ma	road III											
98	ml	Insecticides							8.55		2.5		
99	ac	Insecticides										6	2.28

100	ml	Insecticides maintenance							8.55		2		
101	ac	Insecticides maintenance										3	2.28
102	ma	Application of limestone											
103	ac	Application of limestone										2.5	34.20
104	ma	Aapplication of herbicide											
105	ac	Application of herbicide										5	6.27
106	ma	harrowing											
107	ma	subsoiling											
108	nf	subsoiling										0.3	627.00
109	ac	subsoiling II										0.25	57.00
110	ma	planting											
111	ml	planting labor							8.55		7		
112	o	seedling										1.11	142.50
113	ma	replanting											
114	ml	replanting							8.55		4		
115	o	Seedlings										0.06	142.50
116													
117	ml	Manual weeding Chemistry							8.55		10		

118	ma	Manual weeding Chemistry											
119	ac	Manual weeding Chemistry										4	6.27
120	ma	1st fertilization Cobert. Mec 3 months											
121	nf	1st fertilization Cobert. Mec 3 months										0.2	513.00
122	ma	Chemical weeding Mechanized 6 to 12 months											
123	ac											11	2.28
124	ac											1.5	31.35
125	ma	2nd Fertilization Cobert. Mec 9 months											
126	nf	2nd Fertilization Cobert. Mec 9 months										0.2	541.50
127													
128	ma	Chemical weeding Mechanized											
129	ac	Mechanized Chemical weeding herbicide										5	6.27
130	ma	3rd Fertilization Cober. Mec 15 months											

131	nf	3rd Fertilization Cober. Mec 15 months										0.2	552.90
132													
133	ma	Roads											
134													
135	Ma	harvest										1073.2 104	4.99
136													
137	l	land EU										1	456.00
138													
139	ma	Establishment											
140	ma	Harvest											
141													
142	ml	establishment labour							8.55		40		
143	ml	maintenance year 2							8.55		12.6		
144	ml	maintenance year n							8.55		12.6		
145													
146	ac	herbicides formation										8	14.25
147	nf	fertilization formation										0.86	513.00

148													
149	ac	herbicides maintenance										0	
150	nf	fertilization maintenance										1	330.60
151													
152	l	land										1	456.00
153													
154	vi	Vinasse										110	0.51
155													

All land cost, are derived from (Pedro Valenim Marques, 2008)

Items 1-92 and 154 are derived from (CTBE, 2012), apart from the land costs

Items 95-137 are derived from personal communication Laercio Couto; (Couto, 2013)

Items 139-152 are derived from (Laurent Marie Roger Quéno, Álvaro Nogueira de Souza et al., 2011)

For items 95-152 no information was found about the division of total machinery costs over machinery investment, operational labour and diesel costs. A spread of 68.5% for machinery investment, 16.5% for operational labour and 15% for diesel is used, based on the machinery costs for sugarcane cultivation.

4-SI.7 Scenario for biomass feedstock cultivation

Year	Sugarcane and energycane	Cane trash	Sweet sorghum	Eucalyptus	Elephant grass
1	1-5, 8-10, 12, 14-16[C], 24, 33-36, 43[A], 45-47, 50-55, 60		63-71, 75-79, 82-89, 91	94-114, 116-125, 132, 136	138,139,141, 145, 146, 151
2	15, 17, 19[B], 20[B], 36, 37, 40, 48-51, 56-60	30&31		95, 99, 100, 127-130, 132, 136	139 (2x), 142, 148, 149, 151
3	15, 17, 19, 20, 36, 37, 40, 48-51, 56-60	30&31		95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
4	15, 17, 19, 20, 36, 37, 40, 48-51, 56-60	30&31		95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
5	15, 17, 19, 20, 36, 37, 40, 48-51, 56-60	30&31		95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
6	19, 20, 36, 37, 40, 49-51, 56-60	30&31		95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
7				94, 99, 100, 116-125, 129, 130, 132, 134, 136	139 (2x), 143, 148, 149, 151
8				95, 99, 100, 127-130, 132, 136	139 (2x), 143, 148, 149, 151
9				95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
10				95, 99, 100, 132, 136	139 (2x), 143, 148, 149, 151
11				95, 99, 100, 132, 136	
12				95, 99, 100, 132, 136	
13				95, 99, 100, 132, 136	
14				94, 99, 100, 116-125, 129, 130, 132, 134, 136	

15				95, 99, 100, 127-130, 132, 136	
16				95, 99, 100, 132, 136	
17				95, 99, 100, 132, 136	
18				95, 99, 100, 132, 136	
19				95, 99, 100, 132, 136	
20				95, 99, 100, 132, 136	
21				94, 99, 100, 132, 134, 136	

Chapter 5

Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil

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Abstract

The expansion of the ethanol industry in Brazil faces two important challenges: to reduce total ethanol production costs and to limit the greenhouse gas (GHG) emission intensity of the ethanol produced. The objective of this study is to economically optimise the scale and location of ethanol production plants given the expected expansion of biomass supply regions. A linear optimization model is utilized to determine the optimal location and scale of sugarcane and eucalyptus industrial processing plants given the projected spatial distribution of the expansion of biomass production in the state of Goiás between 2012 and 2030. Three expansion approaches evaluated the impact on ethanol production costs of expanding an existing industry in one time step (one-step), or multiple time steps (multi-step), or constructing a newly emerging ethanol industry in Goiás (greenfield). In addition, the GHG emission intensity of the optimised ethanol supply chains are calculated. Under the three expansion approaches, the total ethanol production costs of sugarcane ethanol decrease from 894 US$/m^3 ethanol in 2015 to 752, 715, and 710 US$/m^3 ethanol in 2030 for the multi-step, one step and greenfield expansion respectively. For eucalyptus, ethanol production costs decrease from 635 US$/m^3 in 2015 to 560 and 543 US$/m^3 in 2030 for the multi-step and one-step approach. A general trend is the use of large scale industrial processing plants, especially towards 2030 due to increased biomass supply. We conclude that a system-wide optimisation as a marginal impact on overall production costs. Utilizing all the predefined sugarcane and eucalyptus supply regions up to 2030, the results showed that on average the GHG emission intensity of sugarcane cultivation and processing is -80 kg CO_2/m^3, while eucalyptus GHG emission intensity is 1290 kg CO_2/m^3. This is due to the high proportion of forest land that is expected to be converted to eucalyptus plantations. Future optimization studies may address further economic or GHG emission improvement potential by optimizing the GHG emission intensity or perform a multi-objective optimization procedure.

5.1 Introduction

The increasing energy demand and the growing awareness of climate change due to fossil fuel related greenhouse gas emissions (GHG) have raised the interest in the use of biomass for energy. As a result, the global annual biofuel production increased significantly from 153 PJ in 1990 to 1988 PJ in 2012, and is likely to grow even further with increasing biofuel demand (IEA, 2013b). World biofuel production is dominated by ethanol, which originates mainly in the United States of America (USA) and Brazil (H. L. Chum et al., 2013; Lamers et al., 2011). The large scale production and consumption of bioethanol in Brazil occurred already since the implementation of the Brazilian Alcohol program in 1975 (Walter, 2008). Due to this experience and know-how, the (mature) industrial processing technology, but also due to the availability of suitable land, Brazil has a large potential to further expand its ethanol production (Lamers et al., 2011; Walter et al., 2011). Currently, more than half of the Brazilian sugarcane based first generation ethanol production is located in the Centre South region, especially São Paulo state (UNICA, 2014). However, the sugarcane production in the states of Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais and Paraná has expanded rapidly in recent decade (UNICA, 2014; Walter et al., 2011). Although currently sugarcane is the biomass feedstock for ethanol production in Brazil, the utilization of new industrial processing technologies using ligno-cellulosic feedstock could enable the use of a wider range of biomass feedstock for ethanol production. Eucalyptus cultivation in combination with novel processing technology holds great promise, especially in regions less suitable for sugarcane cultivation (BNDES, 2008; J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

The expansion of the ethanol industry in Brazil faces two important challenges. First, the aim to reduce total ethanol production costs in order to compete with fossil fuels and other biofuels. Second, the objective of limit the GHG emission intensity of ethanol production, as biofuels are intended to reduce anthropogenic GHG emissions by fossil fuel replacement. Currently, sugarcane based ethanol from Brazil has low production costs and achieves high GHG emission reduction compared to fossil fuels, but also compared to other biofuels produced worldwide (H. Chum et al., 2011). Total ethanol production costs of different biomass crops in Brazil are mainly determined by land cost, biomass yield, logistics, conversion efficiency and scale of industrial processing (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). The total GHG emissions intensity of ethanol production is mainly determined by land-use change (LUC) emissions, pre-harvest burning (common for manual sugarcane harvesting),emissions related to fertilizer application (González-García et al., 2012; J. Seabra et al., 2011), and emissions related to biomass feedstock transportation. Furthermore, the ethanol conversion efficiency, and the GHG emission credits for the co-production of surplus electricity are important to determine the GHG intensity of ethanol production (J. Seabra et al., 2011). In order to assess the costs and GHG performance of the expansion of the ethanol industry in Brazil, these parameters, which are in many cases spatially highly hetereogeneous, should be taken into account.

Strategic biofuel supply chain optimization could be applied to optimise the costs and GHG emissions of potential ethanol production chains in Brazil. A strategic supply chain analysis provides insight into the importance of the different variables in the supply chain design and trade-offs between them, such as the trade-off between transport costs and economy of scale of industrial processing. Numerous studies applied strategic biofuel supply chain optimization procedures to select an optimal bioenergy supply chain design, e.g. (Akgul, Shah, & Papageorgiou, 2012; Cobuloglu & Büyüktahtakın, 2015; Freppaz et al., 2004; Liu, Qiu, & Chen, 2014; Mansuy et al., 2015; Mele, Kostin, Guill, & Jim, 2011; Pettersson et al., 2015; Samsatli, Samsatli, & Shah, 2015). More detailed, strategic optimisation models have been applied to determine the lowest overall biofuel production cost or GHG emissions of the total system design (Giarola, Zamboni, & Bezzo, 2011; Lin, Rodriguez, Shastri, Hansen, & Ting, 2013; Marvin, Schmidt, & Daoutidis, 2013; You, Graziano, & Snyder, 2012).

- The optimization study of Mansuy et al. (2015) used fire-affected forestry biomass in two forest management units in Eastern Canada. The analysis was performed on a 10 by 10 km grid cell scale and due to the low availability of affected forestry biomass, only a limited amount of pellet plants were required.
- Samsatli, Samsatli and Shah (2015) used the United Kingdom as case study region for a hypothetical biomass supply chain optimization for both costs and GHG emissions?. The most important drawbacks are; the limited amount of supply regions (160), the coarse resolution of the supply regions and not considering land demand for other purposes.
- In the study of Pettersson et al. (2015), the emerging biofuel industry using forestry biomass integrated with existing wood using industry was modelled. Although the biomass availability in this study was based on the detailed assessment of Lundmark, Athanassiadis and Wetterlund (2015), which was later aggregated, the study preselected only 51 potential biofuel production sites for whole of Sweden.
- Cobuloglu and Büyüktahtakın (2015) used a multi-objective optimization model to maximize profit of a hypothetical biofuel production facility in Kansas, USA using multiple biomass feedstock. The objective function included both costs and the weighted economic value of several environmental impacts. This study included the expansion of biomass cultivation over other land uses in order to supply the biofuel production facility. The square sourcing area is divided into 440 potential biomass supply regions to supply only one biofuel facility; no other biofuel production facilities are considered.
- The study of (Liu et al., (2014) determined the total profit, fossil energy input, and GHG emissions of biofuel production pathways in China. The results shows the interlinkage of those three elements. However, the study was limited to 25 model supply regions (provinces), of which only 14 were selected as potential locations for biofuel production.

In general, these strategic supply chain analyses are applied for a hypothetical case, for a small amount of biomass supply regions, or present the biomass supply on a very aggregate level. However, the selection of the location, size and type of industrial processing technology of industrial processing plants is determined by the location of biomass supply, transport and type of processing technology to bioenergy (De Meyer et al., 2014). The optimal location of industrial processing plant(s) may differ when optimizing the location of one industrial plant or optimizing a larger region which includes multiple plants. Such system optimization includes the distribution of biomass between the different industrial plants to find the optimal overall solution. The literature reviews of supply chain optimization studies (De Meyer et al., 2014; Sharma, Ingalls, Jones, & Khanchi, 2013) concluded that strategic linear programming models for economic optimization (cost reduction or benefit maximization) constitute the majority of supply chain optimization studies, especially the studies focussed on ethanol production. Sharma et al. (2013) also highlighted the need to develop large-scale case studies and incorporating other measures than economic objectives, such as environmental measures in biomass supply chain analysis. The review by De Meyer (2014) also concluded that in addition to economic objectives also environmental and social objectives, should be included in future work. The reviewed optimization models are usually developed for specific case studies from the producer’s point of view. However, the biomass supply chain is strongly determined by the location of biomass cultivation, transport and processing (De Meyer et al., 2014).

Given the review above the goal of the present study is threefold;

- First: determine the economically optimal location and scale of all ethanol production plants in Goiás, taken into account the expansion of biomass supply regions between 2012 and 2030. The state of Goiás is selected because it has an existing ethanol industry, but still has a high potential to expand the ethanol production in the future (Ferreira Filho & Horridge, 2014). This expansion not only includes the expansion of cultivation area in great detail, but also the increase of biomass yield and improved conversion efficiency to ethanol up to 2030. This is the first strategic supply chain optimization model that uses the detailed results of a land-use change model, and thereby also considers the land use change dynamics of other land uses in a region. None of the reviewed literature considers a real case study area with large evident expansion in the coming decades. Furthermore, the results of the land use change model provide the spatial distribution of expected expansion of biomass supply regions in great detail. This enables to distinguish the variation in costs of biomass cultivation, land, and transport . This was not found in other supply chain optimization studies. In this study, costs for sugarcane and eucalyptus cultivation, transport and industrial processing are determined, comparing the ethanol production by first generation technology to a second generation technology.
- Second, the strategic supply chain optimization model is applied to three different expansion approaches to gain insight in the impact of expanding an existing industry in one step, or several time steps, or constructing a newly emerging ethanol industry in Goiás. This also provides insight in the difference between the economic optimal location and scale of industrial processing and the current supply chain design.

- Third, the resulting supply chain designs are also used to determine the distribution of available biomass among the industrial plants, the economic cost breakdown of ethanol production up to 2030, and the GHG emission intensity of the ethanol produced. The GHG emission intensity of ethanol production is assessed taking into account both land-use change emissions as well as supply chain GHG emissions. The land-use change emissions are determined for each biomass supply region. Based on the detailed biomass supply assessment, a transport module is developed to determine the distance between the biomass supply regions and potential processing locations, including different road types.

The characteristics of the ethanol expansion region are described in section 5-2, followed by a description of the approach, assumptions and equations used in the supply chain optimization in section 5-3. Section 5-4 is an overview of the data used to perform the supply chain optimization. In section 5-5, the results of the optimization are presented, followed by the discussion in section 5-6 and the conclusions in section 5-7.

5.2 Ethanol production in Brazil, sugarcane and eucalyptus cultivation in Goiás.

The production of Brazilian ethanol expanded from 0.6 billion litres in 1975/1976 to 24.0 billion litres in 2012/2013 (UNICA, 2014). In 2014 the total area planted with sugarcane was 10.7 Mha (UNICA, 2014), approximately 1.2% of the Brazilian land territory (Ferreira Filho & Horridge, 2014). Sugarcane is commonly cultivated in ratoons of 6 years with 5 harvests. Sugarcane cultivation regions can be classified into the traditional region (predominantly Sao Paulo state), North-eastern region (mainly the coastal area in the Northeast of Brazil) and the expansion areas (Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais). Availability of land, lower land remuneration, and proper to reasonable conditions for sugarcane cultivation are supporting the expansion of ethanol production in these areas (Eduardo & Xavier, 2012). Next to the expansion of the area also the yield per hectare improved historically (MINISTÉRIO da et al., 2010), and is expected to increase in the future as well (Leal et al., 2012). Due to the phase-out of pre-harvest burning, some areas will be excluded for sugarcane cultivation in the future as the topography restricts mechanical harvesting (Walter et al., 2011).

The sugarcane production in Goiás increased from 13.0 million tonne cane in harvest season 2003-2004 to 62.0 million tonne in season 2013-2014 (UNICA, 2014). In harvest season 2013-2014, the sugarcane has been processed to 1.89 million tonne sugar and 3.88 million cubic metre ethanol (UNICA, 2014). The cultivation in Goiás is mainly in the southern and central municipalities (see SI-1 for a map of current sugarcane cultivation regions and processing locations in Goiás). In the expansion areas, which include Goiás, around 86% of the sugarcane fields are harvested mechanically (Eduardo & Xavier, 2012). In Goiás, 40 sugarcane processing units (both autonomous[14] and annexed[15] plants) are

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[14] An autonomous industrial processing plant is a facility completely dedicated to ethanol production. However, such plant may use sugarcane or molasses from a sugar production facility as feedstock.

currently installed for sugar and ethanol production. Overall, a wide range of processing capacities is installed in Goiás., Recently build industrial plants follow the general trend that larger units are constructed (F. X. Johnson & Seebaluck, 2012). An extensive overview of the installed sugarcane processing plants in Goiás is included in the supplementary information SI.2.

Mello and Rezende (Mello & Rezende, 2013) estimated the total area of planted eucalyptus in Brazil to be around 6.7 Mha, of which 54.5 kha are located in Goiás in 2012. The cultivation of eucalyptus is mainly concentrated in the north-eastern part of Goiás. Eucalyptus is commonly cultivated in 3 consecutive cycles of 7 years (Laércio Couto, 2011). Between 1970 and today, the average yield of Brazilian eucalyptus increased significantly (Stape et al., 2010). Currently, Brazilian eucalyptus is planted for paper and pulp, charcoal, wood products, energy production, oils, tannin extraction, land reclamation, and wind and fire breaks. In Goiás, the eucalyptus production is mainly to supply feedstock for the paper and pulp facilities, sawn wood production and other wood products (IBA, 2014). Currently, there are no ethanol processing facilities utilizing eucalyptus in Brazil. However, with the increase in eucalyptus yield and development of second generation processing in the future, eucalyptus holds great potential for ethanol production in Brazil (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

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[15] An annexed industrial plant is a facility build next to a sugar production facility. The advantages of this set up are to share infrastructure and systems, but it may also offer flexibility in output product ratio.

5.3 Methods

The goal of this study is to optimise the location and size of ethanol production plants for an expanding the biomass supply area, taking into account improvements in biomass yield and conversion efficiency of the two biomass feedstocks up to 2030. The optimization problem is to determine the economic optimal supply chain configuration while utilizing the available biomass cultivated in the biomass supply regions. All costs are expressed in $US\$_{2014}$. The optimization model objective is to minimise total ethanol production costs while respecting the biomass demand and meet model constraints, e.g.: a supply region can never supply more than it is able to produce, or the total amount of biomass transported to a location may not exceed its processing capacity.

The strategic optimization model considers the ethanol supply chain as a network of biomass supply regions which directly deliver to industrial processing locations. Figure 5.1 visualizes the main structure of the supply chain optimization approach, including the data input, intermediate results and final results. The distribution of biomass supply regions (*i*) over the time period 2012-2030 is based on the results of the land use change model PLUC[16], see (J. a. Verstegen et al., 2015). Biomass yield in the supply regions is determined by its suitability for biomass cultivation and the maximum yield in the year of analysis. Biomass yield is also the main variable in land costs, cultivation costs and the total biomass supply in the biomass supply regions considered. By including the transport matrix, the optimization model BioScope[17] is utilized to determine the amount of biomass transported between biomass supply region *i* and the processing plant in location *k.* This amount can be translated into the annual processing capacity or scale of the industrial plant. The total ethanol production costs are the summation of the land costs and cultivation costs of the considered supply regions, transportation costs of the biomass transported between supply regions and the location of industrial processing and the processing costs itself. The key indexes used throughout the model are defined: *i* correspond to the biomass supply regions, and *k* represents the locations of industrial plants. The distribution of biomass supply regions is determined by a land-use change model, as discussed in more detail in section 5.3.1. Thereafter, the expansion approach is described (section 5.3.2), the BioScope model itself is discussed (section 5.3.3), followed by the main elements; biomass cultivation (5.3.4) biomass transport (5.3.5) and industrial processing of biomass (5.3.6).

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[16] PLUC is developed by the University Utrecht as a land use change model. See (Judith Anne Verstegen et al., 2012) for more information on the model development and the utilization of this model for bioenergy crops in Mozambique.

[17] BioScope is developed by the University of Illinois as strategic economic supply chain optimisation model. The optimization procedure of BioScope is a Mixed Integer Linear Programming (MILP) model, using a CPLEX solver in (Lin et al., 2013).

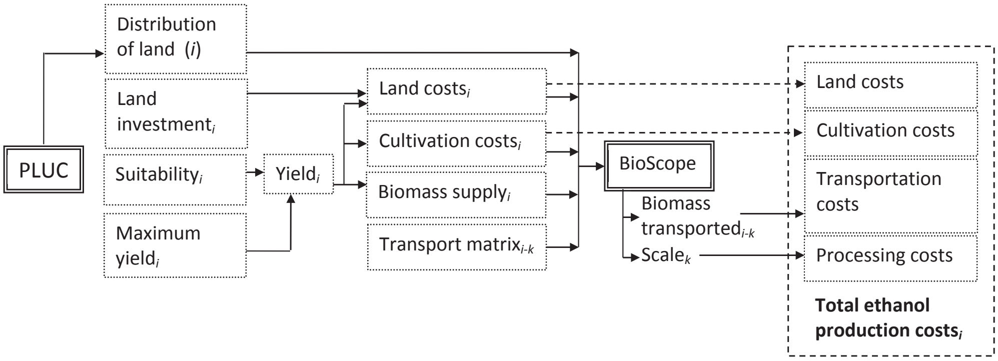

Figure 5-1 The main inputs and outputs of the supply chain optimization model used for the Brazilian ethanol supply chain, i represent the biomass supply regions and k represent the industrial plants.

5.3.1 Amount and distribution biomass supply regions

The distribution of biomass supply regions (*i*) in Goiás is determined by the PCraster Land Use Change model (PLUC model), a spatially explicit land use change model initially described in (Judith Anne Verstegen, Karssenberg, van der Hilst, & Faaij, 2012) and applied for Brazil in (J. a. Verstegen et al., 2015). The demand for different land use types between 2012 and 2030 is determined by the global general equilibrium model MAGNET[18]. Based on the development of, among others, population growth, GDP growth, ethanol yield, and biofuel mandates, MAGNET determines the land claim for different land uses for Brazil, which are transferred to PLUC. For Brazil, PLUC determines annual land use maps between 2012 and 2030 and distinguishes 11 different land use types at 5 by 5 km grid cells (supply regions of 2500 ha) (J. a. Verstegen et al., 2015). The resulting land use maps of PLUC for the state of Goiás were clipped from the Brazil results, and only the biomass supply regions are considered for this optimization study. In this study the sugarcane supply regions are based on the land category 'sugarcane', while the category 'planted forest' is used as representation of eucalyptus supply regions in Goiás. PLUC uses different suitability factors to allocate the land demand (as determined by MAGNET) over Brazil. For sugarcane allocation the suitability factors are, with their calibrated weight between brackets, existence of sugarcane cultivation in the vicinity (0.29), travel time to existing mills (0.28), potential yield (0.22) and the conversion elasticity from other land uses to sugarcane cultivation (0.21). For eucalyptus, the suitability factors are potential yield (0.37), distance to roads (0.34) and existence of planted forest in the vicinity (0.29). These suitability factors are used as fixed, although each factor has a probability distribution; this distribution and the average may change in the future, as discussed in (Judith A Verstegen, Karssenberg, & Hilst, 2015).

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[18] The Modular Applied GeNeral Equilibrium Tool (MAGNET) is developed by the LEI (Landbouw Economisch Instituut) and is based on the LEITAP model (Woltjer et al., 2014)

5.3.2 Expansion approach

Most studies optimize the bioenergy supply chain as a newly emerging industry in an area. However, in Goiás, an existing industry is in place, which influences the optimal location of new industrial plants in that region. A detailed overview of existing sugarcane processing plants is shown in SI-2. To show potential differences, the optimization model procedure is applied for three different expansion approaches: multi-step, one-step and greenfield expansion. The multi-step expansion takes into account existing sugarcane fields and processing plants, and assumes additions of new supply regions and processing plants between 2012 and 2030 in 4 time steps (2015, 2020, 2025 and 2030). Each time step considers the location and scale of industrial processing plants from the previous time step, including the existing industrial plants in 2012 and determines the optimal supply chain design for the newly added plants. The one-step optimization uses the total amount of biomass supply regions available in 2030, and carries out the optimisation in a single step, representing perfect foresight of the location of biomass supply regions. Finally, the greenfield approach considers the same biomass supply regions in 2030, but will not take into account the currently installed industrial processing locations. All approaches consider exogenous improvements of biomass yield, scale of industrial processing and industrial processing conversion efficiency up to 2030, based on data from (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). After the economic optimization, the GHG emission intensity of ethanol is determined, including direct land-use change emissions.

5.3.3 Bioscope model

The expected expansion of the ethanol processing facilities in Goiás is optimised through the use of the BioScope model. See (Lin et al., 2013) for more information on the model structure. The overall modelling objective function for the model is given by Equation 1; minimization of the overall ethanol production costs for all biomass supply regions in Goiás[19]. The equation represents the total cost of ethanol production and includes the land costs (LC_{iy}) biomass cultivation costs (BCC_{iy}), the biomass transport costs ($BTC_{i\text{-}ky}$), and the industrial processing costs (IPC_{ky}). The industrial processing costs include potential revenues of electricity surplus.

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[19] Although the original model formulation of BioScope entailed the use of pre-processing and storage facilities, this is disabled for the application of this model on the Brazilian ethanol industry as sugarcane storage is uncommon in Brazil.

$$\mathrm{EPC_{iy}} = \frac{\mathrm{LC_{iy} + BCC_{iy} + BTC_{i-ky}}}{\mathrm{EtOH_y}} + \mathrm{IPC_{ky}}$$

		Equation 1
EPC_{iy}	Ethanol production cost for supply region i in year y	US$/m^3 ethanol
LC	Land cost in supply region i in year y	US$/tonne biomass
BCC_{iy}	Biomass cultivation cost in supply region i in year y	US$/tonne biomass
$BTC_{i\text{-}ky}$	Biomass transport cost between biomass supply region i and industrial plant location k in year y	US$/tonne biomass
$EtOH_y$	Biomass conversion efficiency in year y	m^3 ethanol/tonne biomass
IPC_{ky}	Industrial processing cost of plant k in year y	US$/m^3 ethanol

The data regarding biomass availability in the biomass supply regions (*i*), the costs data regarding cultivation, transport and the capital and operational costs of biomass processing are exogenously determined and supplied to the BioScope optimization model. The key output of the model is a list of the locations and scales of the industrial processing facilities and a list of the amount of biomass transported from each biomass region(s) to the existing and selected new industrial processing location(s). These results are later used to determine the total ethanol production costs per biomass supply region, as depicted in Figure 5-1.

5.3.4 Biomass supply

The total potential biomass availability of sugarcane or eucalyptus in each supply region (i) is a function of suitability and potential maximum yield, as described in Equation 2. The agro-ecological suitability is based on the suitability data of GAEZ, see (Geze Toth, Bartosz Kozlowski, Sylvia Prieler, 2012; IIASA/FAO, 2012).

$$\mathrm{Sup_{iy}} = \mathrm{S_i} \times \mathrm{M_Y} \times \mathrm{A}$$

		Equation 2
Sup_{iy}	Biomass supply potential in region i in year y	tonne/year in biomass supply region i
S_i	Suitability of land at location i	% of maximum biomass yield
M_Y	Maximum attainable yield in year y	tonne/ha-year
A	Area per biomass supply region	2500 ha/ biomass supply region

5.3.5 Biomass cultivation

The biomass cultivation costs of sugarcane and eucalyptus are determined using Equation 3 and supplied as input for the BioScope model. Based on the detailed cost assessment of (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014), a non-linear relationship between biomass cultivation costs and biomass yield was established. For the current study, the biomass cultivation costs are simplified to Equation 3, in which biomass yield is the important (spatial) variable. Cost factor *a* includes the costs for plantation management per hectare, e.g. soil preparation, planting, application of herbicides. Cost factor *b* includes the use of fertilizers and harvesting, expressed in

US$/tonne. Land costs consider the land remuneration (spatially heterogeneous) and the land conversion costs, and are separately determined, see SI-4 for the calculation on land value. For both factor *a* and *b*, all costs are already discounted with an discount rate of 12%, similar to (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). Cost component *c* includes all additional costs, expressed as a percentage of the total biomass cultivation costs.

$$\mathrm{BCC_{iy}} = \frac{\left(\frac{\mathrm{a}}{\mathrm{Y_{iy}}}\right) + \mathrm{b}}{(1 - \mathrm{c})}$$

Equation 3

BCC_{iy}	Biomass cultivation cost in biomass supply region i in year y	US$/tonne
a	Cost for areal management practices and inputs	US$/ha-year
b	Cost per tonne biomass	US$/tonne
c	Administrative / other cost	%
Y_{iy}	Biomass yield in biomass supply region i in year y	Tonne/ha-year

The expansion of the biomass supply regions results in land use change from cropland, pasture or forested land to biomass cultivation areas. This could result in land use change emissions due to a change in carbon stock. In this study, the IPCC approach is applied to determine carbon accumulation or carbon emissions due to land use change (IPCC, 2006). This approach includes the carbon stock change in above ground biomass, below ground biomass, and soil organic carbon. For each potential biomass supply region the carbon stock change is the difference between the new carbon stock and the carbon stock of the biomass supply region in 2006, which is considered the former carbon stock. The year 2006 is the most recent year for which the land use map and agricultural databases were available to create a detailed initial land use map (J. a. Verstegen et al., 2015). As specified by Equation 4, the carbon stock change is annualized by 20 years, similar to the IPCC and the RED policy for liquid biofuels (EC European Commission, 2010; IPCC, 2006) and thereafter converted to CO_2 emissions by the factor (44/12).

$$\mathrm{C_i} = \frac{\mathrm{C_{former}} - \mathrm{C_{new}}}{\mathrm{A_{period}}} \times (\mathrm{C_{conversion}})$$

Equation 4

C_i	Carbon stock change due to land conversion in region i.	tonne CO_{2eq} / year
C_{former}	Carbon stock former land use	tonne carbon/ha
C_{new}	Average carbon stock of new biomass plantation	tonne carbon/ha
A_{period}	Annualizing period; to annualize the land use change emissions	20 years
$C_{conversion}$	Carbon dioxide to carbon conversion ratio	44/12

The GHG emissions of biomass cultivation include the consumption of diesel, fertilizers and agrochemicals and are shown in Equation 5. A detailed overview of cultivation inputs over the lifetime of a sugarcane or eucalyptus plantation and the GHG emission intensities is provided in SI-3. The emission intensities of the fuels, fertilizers and chemicals are based on emission databases, and other scientific literature, see SI-3 for a detailed overview. The GHG emissions related to fertilizer consumption, the use of agro-chemicals and the application of vinasse, filtercake and forestry residues are considered and expressed in an emission factor a or b. GHG emission factor a includes the annualised GHG emissions per hectare, while factor b includes all GHG emissions per tonne biomass.

$$\mathrm{BCE_{iy}} = \left(\frac{\mathrm{a}}{\mathrm{Y_{iy}}}\right) + \mathrm{b} + \left(\frac{\mathrm{C_i}}{\mathrm{Y_{iy}}}\right)$$

		Equation 5
BCE_{iy}	Biomass cultivation GHG emissions in biomass supply region i in year y	gram CO_{2eq} /tonne
a	Annualised GHG emissions per hectare	gram CO_{2eq} /ha-year
b	GHG Emissions per tonne biomass	gram CO_{2eq} /tonne
C_I	Carbon stock change due to land conversion in region i	gram CO_{2eq} /ha-year
Y_{iy}	Biomass annual yield in supply region i in year y	Tonne/ha -year

5.3.6 Biomass transport

Biomass transport between biomass supply regions and industrial processing locations is performed by truck. Transportation cost and transport emissions are the sum of costs or emissions for transporting biomass from the field to the industrial processing plants over the road network in Goiás. In this study, three different road types are distinguished: primary asphalt roads (1), secondary roads (2) and dirt roads (3), each with a specific average speed and fuel consumption. For each potential location of an industrial processing facility, a map is computed that indicates for each field the accumulated costs (or emissions) of transporting the feedstock to this industrial plant location. Herein, it is assumed that the truck will take the fastest route. The calculation of this stack of maps is automated using the PCRaster Python framework (Karssenberg, Schmitz, Salamon, de Jong, & Bierkens, 2010). Next, the stack of maps is converted to a single matrix, indicating the total transport costs (BTC_{ik}) or biomass transport emission (BTE_{ik}) from each biomass supply region to each potential location of industrial plant. The used data is derived from (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014), and considers a relationship between truck velocity, distance, and biomass transport costs by truck. The total biomass transport cost consider the transport costs of the three different road types (road type 1, 2 and 3), as shown in Equation 6. Cost factor *a* represent the transportation costs which are time depended, cost factor *b* represents the costs per km transhipment, both already account for the empty return trip. Cost item *c* present the fixed transportation costs, for example associated with loading and unloading.

$$\mathrm{BTC_{ik}} = \sum_{R}\left(\left(\left(\frac{a}{V_R}\right) + b\right) \times D_{i-k}\right) + c$$

		Equation 6
BTC_{ik}	Biomass transportation cost between biomass supply region i and industrial processing plant location k	US$/tonne
a	Cost factor a	US$/tonne-hour
b	Variable biomass transport cost per tonne-km biomass transported	US$/tonne-km
c	Fixed transportation cost per tonne biomass	US$/tonne
D_{i-k}	Distance between biomass cultivation region in i and industrial plant in location k	Km
V_R	Truck speed on specific road type (R: 1, 2 and 3)	Km/hour

Greenhouse gas emissions biomass transport.
Total GHG emissions of biomass transport include the GHG emissions of the specific diesel consumption, related to truck speed on the distinguished road types for the transport trajectory between supply region and industrial location. Equation 7 describes the total GHG emission of biomass transport between the biomass supply region and an industrial processing location. As the distance (D_{i-k}) is for a single trip, the empty return is taken into account by an empty return factor.

$$\mathrm{BTE_{ik}} = \sum_{R}\left(\left(\frac{D_{use-R} \times D_{emissions} \times F_{return}}{Load}\right) \times D_{i-k}\right)$$

		Equation 7
BTE	Biomass transportation emissions	gram CO_{2eq}/tonne
D_{use-R}	Diesel use of the truck on selected road type (R: 1, 2 and 3)	l/km truck
$D_{emissions}$	GHG emission intensity of diesel	CO_{2eq}/l
F_{return}	Factor empty return trip	[-]
Load	Truck biomass load	Tonne/truck
D_{i-k}	Total distance of a single trip between biomass supply region (i) and industrial plant (k)	Km

5.3.7 Industrial processing of biomass to ethanol and electricity

The industrial processing costs of biomass to ethanol are a combination of capital depreciation, operational costs and electricity revenues. The capital costs of an industrial processing facility is assumed to be heavily dependent upon the scale of the facility. Industrial processing scale is an important variable within the BioScope model. To enable the embedding of this variable into the linear optimization model, a linear relationship between the total capital investment and industrial scale is assumed, similar to (Lin et al., 2013). See Equation 8 for this linear relationship, where capital cost factors *a* and *b* depend upon the type of industrial processing plant, and also the operational costs and revenues for electricity surplus are taken into account in the total processing cost. The scale of industrial processing plants are restricted by a maximum scale: when the biomass supply to a processing plant reaches this maximum capacity, the biomass is redirected to another industrial processing facility. The operational costs of industrial processing include variable costs of operations related to labour, utilities and maintenance. As an approximation, it is assumed that the operational expenses are linearly dependent upon the processing capacity of the industrial plants. Both the capital investment and operational costs are based on the detailed economic analysis, performed by (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). The map of the current situation (year 2012) of the ethanol industry in Goiás shows that industrial processing facilities are in, or in close proximity of biomass supply regions. Therefore, all biomass supply regions in Goiás are considered as candidate locations of industrial processing. Considering all regions in Goiás as candidate locations of industrial processing would prolong the computing time considerably.

$$\mathrm{IPC_k} = \frac{\alpha\big((\mathrm{a} \times \mathrm{S_k}) + \mathrm{b}\big)}{\mathrm{output}} + \mathrm{opex} - \mathrm{elec}$$

Equation 8

IPC_K	Scale dependent industrial processing cost of industrial facility k	US\$/m^3 ethanol
α	Annuity factor	%
a	Capital investment cost factor a of industrial scale k	US\$/tonne-hour
b	Capital investment cost factor b of industrial scale k	US\$
S_k	Scale of industrial processing plant k	Tonne/hour
opex	Operational expenses of industrial processing	US\$/m^3 ethanol
Elec	Electricity revenues	US\$/m^3 ethanol
Output	Annual ethanol output of the plant in location k	m^3 ethanol/year

GHG emission of industrial processing

To determine the GHG emissions of industrial processing, the GHG emissions related to the chemical and the energy inputs are taken into account (see Equation 9). The GHG emissions related to the construction of the industrial plant are neglected as these are difficult to estimate and play a minor role (Isaias de Carvalho Macedo et al., 2004). The GHG emissions of industrial processing are based on other scientific publications and expressed per tonne of biomass input or per m^3 ethanol output. When considering the GHG emissions per tonne biomass input, the ethanol production efficiency is accounted for. Avoided emissions related to electricity surplus are included in the operational GHG emissions, $I_{GHG\text{-}t}$ or $I_{GHG\text{-}v}$.

$$\mathrm{GHG}_{\mathrm{processing}} = \frac{\mathrm{I}_{\mathrm{GHG-t}}}{\eta} \quad \text{or} \quad \mathrm{I}_{\mathrm{GHG-v}}$$

		Equation 9
$\mathrm{GHG}_{\mathrm{processing}}$	Greenhouse gas emissions of industrial processing of biomass to ethanol	gram CO_{2eq}/m^3 ethanol
$I_{GHG\text{-}t}$	GHG emission of industrial processing per tonne input	gram CO_{2eq}/ Tonne
η	Ethanol conversion efficiency	m^3 $_{ethanol}$ /tonne biomass
$I_{GHG\text{-}v}$	GHG emission of industrial processing per cubic metre ethanol	gram CO_{2eq}/ m^3 ethanol

Ethanol yield

Although industrial processing plants all utilizes the same industrial technology, the ethanol yield per tonne of biomass changes over time for both sugarcane as well as eucalyptus, as sugar content increases and industrial efficiencies of new plants are assumed to be higher compared to older facilities. The ethanol yield is defined by Equation 10 and include the increase in sugar content, conversion efficiency, and maximum ethanol yield per tonne of biomass. For eucalyptus, the sugar content in Equation 10 is not used, but the industrial processing efficiency does improve, and the maximum ethanol yield is expressed as ethanol yield per tonne biomass.

$$\mathrm{EtOH_y} = \mathrm{sc_y} \times \eta_c \times \max$$

		Equation 10
$EtOH_y$	Ethanol yield on biomass in year y of industrial processing	m^3/tonne biomass
Sc_y	Sugar content of sugarcane in year y	Kg sugar/tonne sugarcane
η_c	Conversion efficiency of industrial processing of industrial plant *k* in year of construction.	%
max	Maximal ethanol yield on sugar / biomass for sugarcane or eucalyptus	m^3 ethanol / kg sugar or tonne biomass

5.4 Data input

5.4.1 Biomass supply regions

As indicated in Figure 5-1 the prime data input is the list (location and biomass production of the supply regions) of biomass supply regions (*i*), which expand between 2012 and 2030 as defined by the land use model PLUC. The amount of biomass supply regions (*i*) taken into account per year, and the parameters to determine the potential biomass supply of sugarcane or eucalyptus per supply region (Sup_i) using Equation 2, are shown in Table 5-1.

Table 5-1 Biomass supply parameters

		Sugarcane	Eucalyptus	Reference
Total biomass supply regions (kha)	2012	339 (848)	-	(Judith Anne Verstegen et al., 2012)
	2015	404 (1010)	141 (353)	
	2020	658 (1645)	347 (868)	
	2025	719 (1798)	537 (1343)	
	2030	780 (1950)	751 (1878)	
Agro-ecological suitability factor range (all years)[A]		0.118 – 0.521	0.284 – 0.740	(IIASA/FAO, 2012)
Maximum potential biomass yield for 2012		180 TC/ha-year[B]	24 dry tonne/ha-year[C]	
Annual biomass yield increase[D]		0.9 % per year	2 % per year	(J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014)

[A] Agro-ecological suitability entails the suitability of this supply regions for the cultivation of sugarcane or eucalyptus, expressed as yield factor, e.g. percentage of maximum attainable yield.

[B] The maximum biomass yield of sugarcane is chosen as such that the total sugarcane supply in 2012 matches the total annual production of 2012 (UNICA, 2014).

[C] Maximum biomass yield of eucalyptus is selected to yield an average eucalyptus yield in line with the expected average yield of eucalyptus as presented by (Bracelpa, 2009).

[D] The increase of sugarcane and eucalyptus yield is based on yield trends in (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

5.4.2 Biomass cultivation costs and GHG emissions

Table 5-2 summarizes the parameters used to determine the cultivation costs and GHG emissions of sugarcane and eucalyptus cultivation, using Equation 3 and 5. The values summarise the detailed cultivation cost breakdown of sugarcane and eucalyptus, shown in (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). See appendix SI-3 and SI-4 for a more detailed overview of land costs and overview of the cultivation costs and GHG emissions respectively. The economic parameters in Table 5-2 include components expressed per ha (subtotal *a*) and parameters expressed per tonne of harvested biomass (subtotal *b*). Table 5-2 also includes the GHG emissions of machinery utilization and agricultural or silvicultural inputs of sugarcane and eucalyptus cultivation are presented.

Table 5-2 Economic and GHG emission data parameters for the cultivation of sugarcane and eucalyptus.

Biomass type	Parameter (a, b or c corresponds to parameter in Equation 3 or 5)	Economic value	Unit	GHG value	Unit
	Subtotal (*a*) land	3015 – 6200[A]	US$/ha	-	
sugarcane	Subtotal (*a*)	1432[B]	US$/ha	366[E]	kg CO_2/ha
	Subtotal (*b*)	17.93[C]	US$/tonne	15.22[F]	kg CO_2/TC
	Administrative cost (*c*)	6%[D]	%	-	
eucalyptus	Subtotal (*a*)	450.47[B]	US$/ha	111[G]	kg CO_2/ha
	Subtotal (*b*)	6.593[C]	US$/tonne	15.05[H]	kg CO_2/tonne dry
	Administrative cost (c)	6%[D]	%		

[A] Land costs in Goiás vary according to current land use and vary per region in Goiás (FNP Informa economics, 2012), see SI-4 for a detailed overview of the considered land costs.

[B] Subtotal of cultivation costs which are related to the application of limestone, herbicides and insecticides.

[C] Subtotal of cultivation costs expressed in US$/tonne.

[D] An additional 6% is included in the cultivation costs to account for administrative expenses, similar to (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[E] Include the GHG emissions of diesel consumption (excluding harvesting) and the GHG emissions related to the applications of limestone, herbicides and insecticides.

[F] Include the GHG emissions for diesel consumption related to harvesting, fertilizer application (including production), filtercake and vinasse application and trash left in the field.

[G] Include the GHG emissions of diesel consumption (excluding harvesting) and the GHG emissions related to the applications of limestone and herbicides.

[H] Include the GHG emissions of diesel consumption related to tree harvesting, fertilizer application (including production) and forestry residues left onsite.

5.4.3 Biomass transport

The total transport distance, between biomass supply regions and potential locations of industrial processing plants, is the sum of the distances of different road types. BioScope input is the transport matrix which describes the total transport costs per tonne biomass between supply regions and potential locations of industrial processing plants. Potential locations for industrial processing include all biomass supply regions. Truck velocity is considered as the main determinant for difference in transportation costs, see Table 5-3.

Table 5-3 Economic and greenhouse gas emission data for biomass transport.

			Road type		
			Dirt roads	Secondary road	Highway
Speed[A]			15 km/h	55 km/h	80 km/h
Diesel consumption[B]		**l/km**	0.83	0.37	0.90
Truck loading[C]		**tonne/ truck**	30		
Transport cost parameters[D]	Subtotal (*a*)	**US$/ tonne-km**	2.68		
	Subtotal (*b*)	**$US\$_{cent}$/ tonne-km**	6.35	4.07	3.56
	Subtotal (*c*)	**US$/tonne**	2.0		
GHG emissions[E]		**gram CO_{2eq}/tonne-km**	145	65	70

[A] Different truck speeds have been selected to account for the main road types for biomass transport.

[B] Diesel use is based on (Barth, Youngslove, & Scora, 2005) in which the diesel consumption as function of truck velocity is plotted. The diesel use is adjusted to a larger truck size.

[C] Truck loading of a sugarcane truck is approximately 30 tonne wet cane/truck (CTBE, 2012)

[D] More detailed information about the build-up of different costs parameters, see supplementary information SI-5.

[E] Truck transport emissions are determined with Equation 7, using a factor for empty return of 1.4)meaning the fuel consumption for an empty trip is only 40% of a full loaded trip', similar to (Hamelinck et al., 2005). Emissions factor of diesel in Brazilian transport is based on the GHG intensity of diesel production and consumption 24.1 gram C/MJ diesel (Macedo et al., 2008) and Higher Heating Value of diesel of 44MJ/l, as specified by (Hamelinck et al., 2005)

5.4.4 Industrial processing of biomass to ethanol

The capital and operational cost parameters of first generation sugarcane processing and second generation eucalyptus processing are presented in Table 5-4. The capital expenses of industrial processing are scale dependent but non-linear due to the scale factors of the different components (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). To consider the economy of scale in the linear optimization model, two scale ranges are considered in this analysis to fit the non-linear relationship, similar to (Lin et al 2013). Operational costs include chemicals, labour, and operating & maintenance, and are expressed in US$/tonne biomass input. Electricity is produced with a residue-fed steam boiler (86% thermal efficiency (Dias, Cunha, et al., 2011)), followed by a condensing extracting steam turbine. The residual sugarcane bagasse (for first generation) and unreacted solids (for second generation technology) are utilized in the cogeneration unit. A part of the generated steam is extracted for the distillation process. For first generation industrial processing, the cogeneration unit generates an electricity surplus of 81.6 kWh/tonne cane. In second generation industrial processing, the ethanol conversion efficiency is assumed to increase over time resulting in less unreacted solids available for steam production in the future, Therefore, the surplus electricity reduces from 428 kWh/tonne in 2015 to 220 kWh/tonne in 2030. Electricity revenues expressed in US$/tonne biomass input, are based on the electricity surplus and electricity prices.

Table 5-4 Economic and greenhouse gas emissions data of industrial processing of first and second generation processing.

			Scale range	
First generation			100-999 TC/hour[A]	1000-2000 TC/hour
		Days of operation	170 days/year[B]	
	Capex cost parameter a	**US$**	75.57[C]	59.09 [C]
	Capex cost parameter b	**US$**	40 x 10^{6} [C]	100 x 10^{6} [C]
	Operational costs	**US$/tonne cane**	8.88[D]	
	GHG emissions	**kilogram CO_2 /tonne cane**	4.45[E]	
	Electricity surplus	**kWh electricity/ tonne input**	81.6[F]	
	Ethanol yield	**liter/tonne cane**	83 – 92[G]	
	Maximum capacity	**Mtonne cane/year (year)**	4.0 (2012) / 5.0 (2020) / 5.5 (2030)[H]	
Second generation		**scale range**	25 - 74 dry tonne/hour[I]	75 - 500 dry tonne/hour[I]
		days of operation	300 days/year[J]	
	Capex cost parameter a	**US$**	469.01[C]	394.40[C]
	Capex cost parameter b	**US$**	40 x 10^{6} [C]	80 x 10^{6} [C]
	Operational costs	**US$/$m^3$ ethanol**	153[K]	
	GHG emissions	**gram CO_2/Liter**	44.52[L]	
	Electricity surplus	**kWh electricity/ tonne input**	428 – 220[M]	
	Ethanol yield	**liter/tonne biomass**	293 – 377[N]	
	Maximum capacity	**Mtonne dry biomass/year (year)**	0.72 (2015) / 1.46 (2020) / 3.06 (2030)[O]	

[A] Low range and high range of sugarcane processing capacity of first generation industrial processing.

[B] Operational window is related to the sugarcane harvesting window, similar to (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[C] Capital expenses parameters a and b, see Equation 10, are derived from (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014), in which the capital costs of first and second generation industrial processing is discussed, including scaling factors for the major components of the industrial processing plant.

[D] Total operational expenses of first generation processing is 8.88 US$/tonne cane (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[E] GHG emissions of ethanol production is 2.6 gram CO_2/MJ and an ethanol yield of 81.1 litre/TC (J. E. a. Seabra, Tao, Chum, & Macedo, 2010).

[F] For first generation industrial processing, surplus electricity is produced using sugarcane bagasse as feedstock for a high pressure boiler (86% thermal efficiency (Dias, Cunha, et al., 2011)), followed by steam turbine. Based on the data provided by Dias et al (Dias, Cunha, et al., 2011), this setup results in an electricity surplus of 81.6 kWh/tonne cane.

[G] Ethanol yield increasing from 83 L/TC in 2015 to 92 L/TC in 2030, due to increasing sugar content 14.9-16.0 and increasing industrial efficiencies (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[H] Maximum industrial processing capacity increases over time; 4 million tonne cane/year in 2012, 5.0 M tc/yearin 2020 to 5.5 Mtonne cane/year in 2030 (MME, 2013)

[I] Low range and high range of eucalyptus processing capacity of second generation industrial processing.

[J] Operational window similar to (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[K] Total operational expenses of second generation processing is 153 US$/tonne biomass input (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[L] GHG emissions of second generation ethanol processing of eucalyptus is expressed by (Hoefnagels et al., 2010) as 2.1 gram CO_2/MJ ethanol.

[M] For second generation processing, surplus electricity is produced by using the lignin fraction and unfermented sugars as fuel for the boiler (thermal efficiency 86%). Steam is used in a steam turbine to produce electricity, although part of the steam is extracted for distillation (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[N] The ethanol yield of eucalyptus processing increases from 293 L ethanol/dry tonne eucalyptus to 377 L/dry tonne (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014).

[O] Maximum industrial processing capacity of second generation increases over time by following the trend of HHV biomass input as specified by (Hamelinck et al., 2005)

5.5 Results

5.5.1 Maps of the expansion of ethanol processing plants

In Figures 5-2 to 5-6, maps show the biomass supply regions and the industrial processing facilities in 2030. The current and expanded biomass supply regions are highlighted with shades of green. As the biomass supply regions are pre-determined, the three different expansion approaches are based on the same distribution of supply regions in 2030. The total biomass supply in 2030 is higher compared to 2012 due to improved biomass yield as well as the expansion of biomass supply regions. The optimisation model locates industrial plants according to available biomass supply. Industrial plants are depicted with a red dot (existing industrial plants for sugar or ethanol production) or black dot (new industrial plants for ethanol production). The capacity of industrial processing plants is depicted by the size of the dot. Five different size ranges are distinguished. Biomass supply regions with identical colour deliver to the same industrial plant, supply regions with a hatched pattern deliver biomass to more than one industrial plant. As the optimization is applied for different time steps until 2030, in each time step the industrial processing capacity matches the total biomass supply.

For the maps of sugarcane cultivation in Figures 5-2, 5-3 and 5-4, the expansion of the sugarcane supply regions is mainly northwest of the existing sugarcane fields in the South of Goiás, depicted by the zoom area in Figures 5-2 to 5-4. Especially in the new biomass supply regions (highlighted in the zoom area), large scale industrial processing plants are proposed by the optimization model. In general, the optimisation model selects large industrial processing plants due to the economies of scale; only in regions which are not able to supply large industrial plants with enough sugarcane, the industrial scale is smaller. For the multi-step (Figure 5-2) and one-step approach (Figure 5-3), the already existing industrial plants are complemented with new industrial plants to process the total biomass supply in 2030. The multi-step optimization approach (Figure 5-2) results in a total of 59 plants compared to 56 industrial processing plants for the one-step optimization approach (Figure 5-3). The multi-step approach results in more industrial plants, as yield increases between each time step but the capacity of industrial plants is fixed once constructed. To utilize the additional biomass supply in each time step, new industrial plants with relatively small processing capacity are needed. The greenfield optimization approach (Figure 5-4), yields 29 industrial processing plants, slightly less compared to the current situation (depicted in 5-SI-1). The greenfield approach (Figure 5-4) results in the lowest number of industrial plants due to the preference of large scale plants: around half of the total industrial plants have the maximum allowable industrial capacity in 2030. Although there are small differences among the expansion approaches in the location and scale of industrial plants, the distribution of available biomass differs considerably. When biomass supply regions are very isolated from industrial processing plants or other supply regions, the available biomass is transported over longer distances instead of building a small industrial plant due to the high investment costs of small industrial plants. For example, in the North of Goiás only one new industrial plant is added to process the additional supply in both the multi-step and one-step optimization approach.

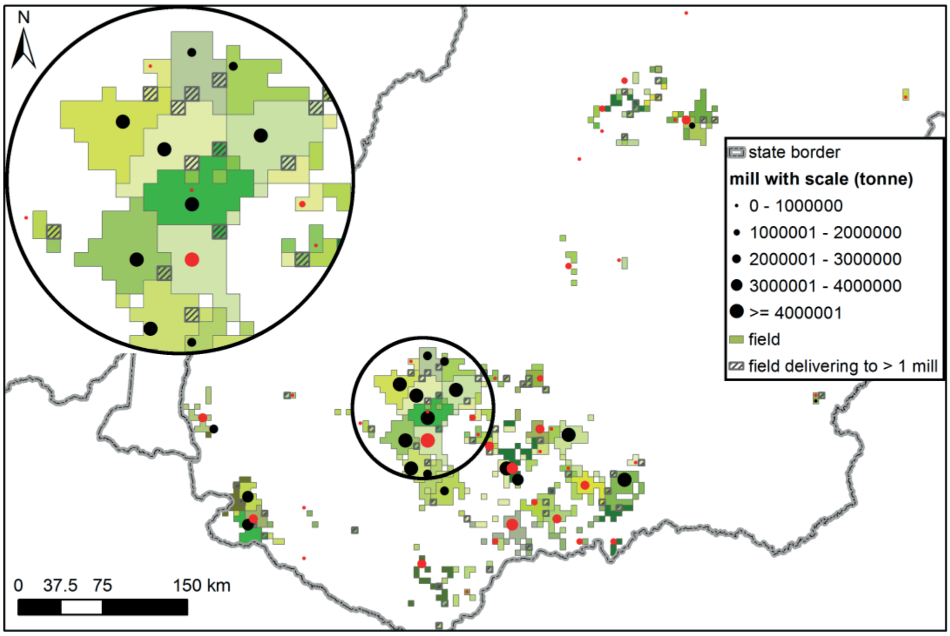

Figure 5-2. Map of the multi-step optimization approach (2012, 2015, 2020, 2025 and 2030) of the sugarcane supply regions in green and industrial plants (red circles represent existing industrial plants for sugar or ethanol production, black circles represent new industrial plants for ethanol production) in 2030.

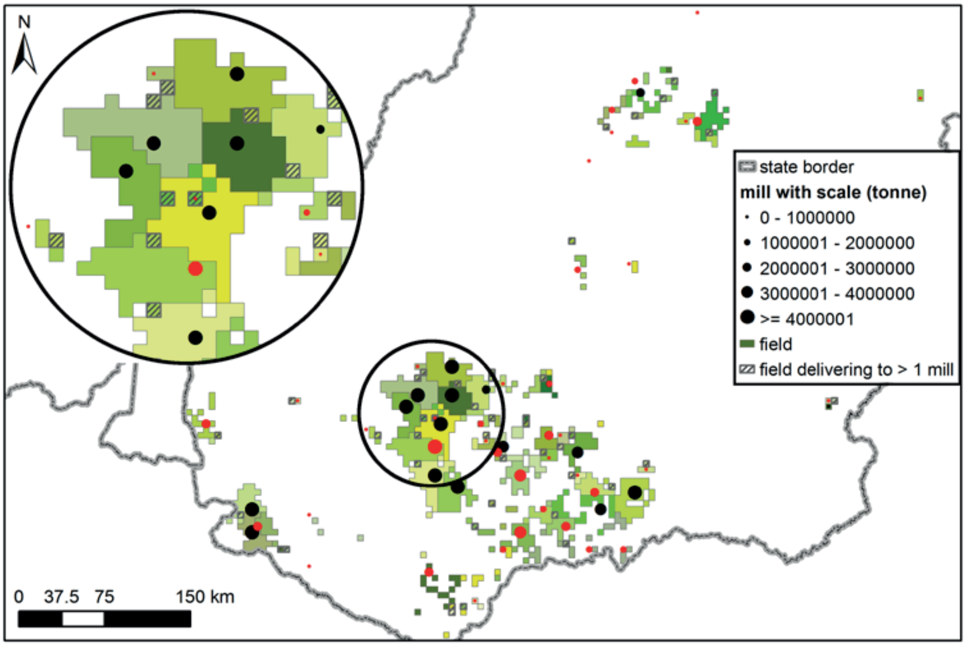

Figure 5-3. Map of of the one-step optimization approach (2012-2030) of the sugarcane supply regions in green and industrial plants (red circles represent existing industrial plants for sugar or ethanol production, black circles represent new industrial plants for ethanol production) in 2030.

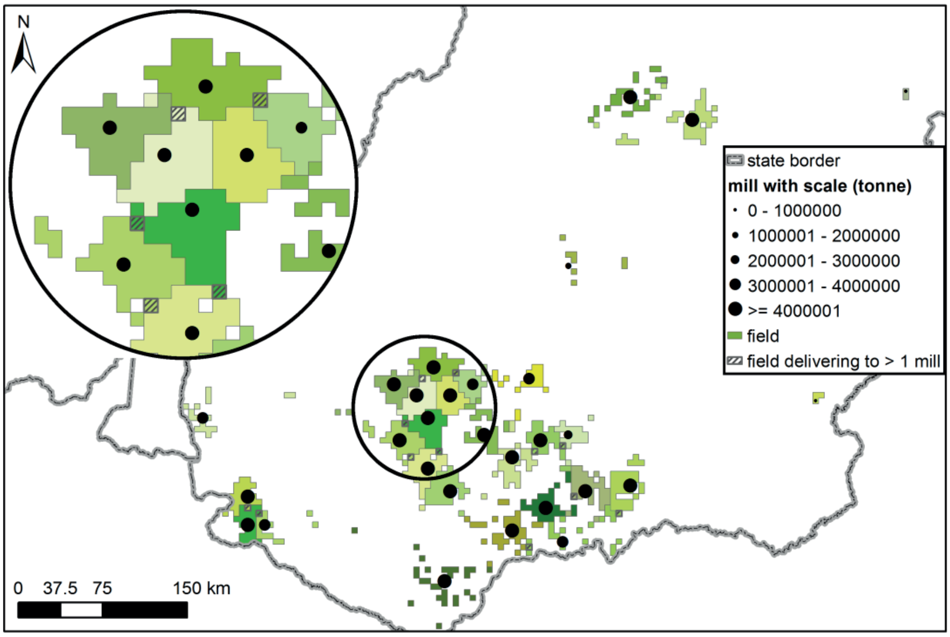

Figure 5-4. Map of the greenfield optimization approach (2030) of the sugarcane supply regions in green and industrial plants dedicated to ethanol production in 2030.

Maps of the expansion of eucalyptus cultivation for ethanol production in the state of Goiás are depicted in Figure 5-5 and 5-6. Eucalyptus cultivation is mainly clustered in the north-eastern part of Goiás. As no existing eucalyptus to ethanol processing plants are currently in place in Goiás, only the multi-step (Figure 5-5) and one-step (Figure 5-6) optimization approach were carried out. The multi-step optimization approach results in the construction of 42 plants compared to 23 industrial processing plants for the one-step optimization approach. For the multi-step optimization approach (Figure 5-5), the eucalyptus supply increases rapidly over time due to a fast increase in supply regions as well as eucalyptus yield improvement. Due to the clustered eucalyptus supply and economies of scale, the optimization model selects large scale industrial processing plants.

When comparing sugarcane cultivation and processing to eucalyptus cultivation and processing, the optimization prefers large scale industrial processing for both crops. The differences in total amounts of industrial plants of the multi-step and the one-step approach, when comparing eucalyptus to sugarcane, is due to the rapid expansion of eucalyptus supply regions, importance of capital investment in total ethanol production costs of second generation ethanol, and the large allowable industrial scale for industrial processing. To limit transportation costs, the industrial processing plants are placed in biomass supply regions with highest biomass yield. In other words, to obtain the lowest total transportation costs, the region with the highest yield supply is selected for the location of an industrial plant.

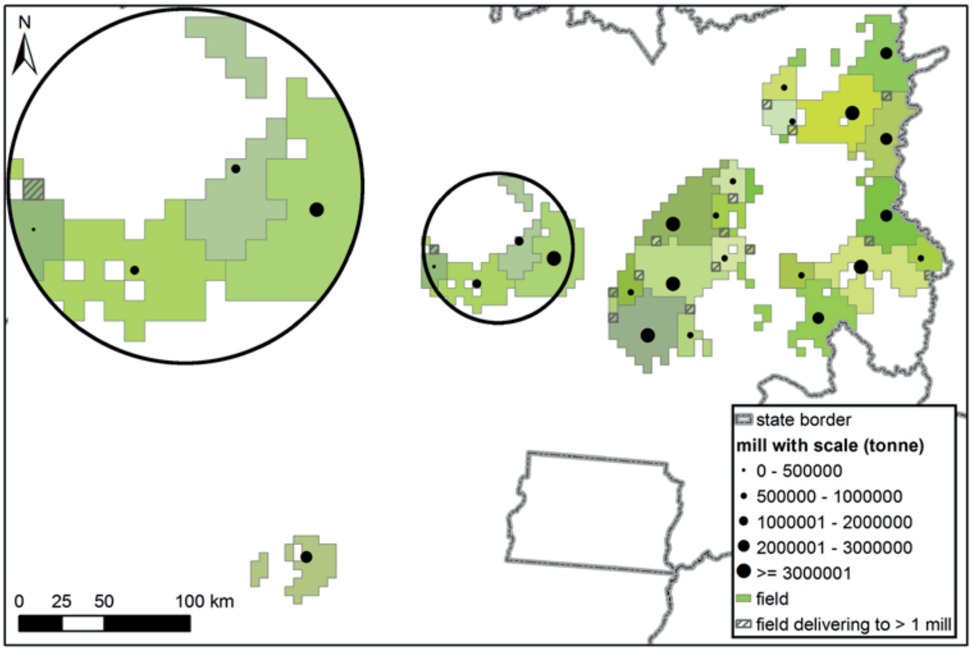

Figure 5-5. Map of the one-step expansion approach (2030) of the eucalyptus supply regions in green and industrial plants represented by black circles.

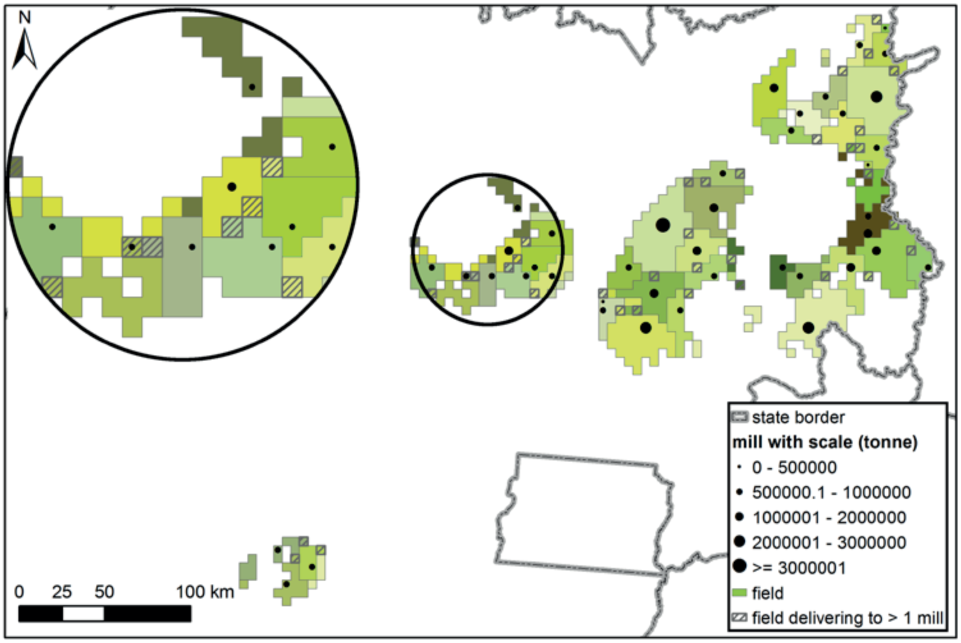

Figure 5-6. Map of the multi-step expansion approach (2030) of the eucalyptus supply regions in green and industrial plants represented by black circles.

5.5.2 Cost breakdown of ethanol production

Figure 5-7 presents the average ethanol production cost breakdown for the expansion of sugarcane and eucalyptus and includes costs for land, cultivation, transport and industrial processing for the multi-step expansion (different time steps up to 2030), one-step expansion (solely 2030), and the greenfield expansion approach (solely 2030). Note that the existing ethanol production facilities are excluded from the cost breakdowns. Only biomass supply regions connected to the proposed new industrial processing plants are considered in Figure 5-7, resulting in a small difference in cultivation costs when comparing the multi-step and one-step approach. The total ethanol production costs of 2012 is added as reference value. This value represents the total ethanol production costs determined with the optimization model including all available sugarcane supply regions and existing industrial processing plants in 2012. Under the three different expansion approaches the production costs of sugarcane ethanol decrease from 894 US$/m^3 ethanol in 2015 to 752, 715 and 710 US$/ m^3 ethanol in 2030 for the multi-step, one-step and greenfield expansion respectively.

In general, the ethanol production costs for sugarcane processing decline due to yield improvement and the construction of large scale industrial plants. The expansion of sugarcane supply regions between 2015 and 2020 is allocated by PLUC to high biomass yield regions, while after 2020, lower yielding biomass supply regions are taken into cultivation, resulting, on average, in higher cultivation costs in 2025. When comparing the total ethanol production costs in 2030, the main difference among the different expansion approaches is the variation in size of plants, which results in lower capital investment for industrial processing.

For eucalyptus, the ethanol production costs decrease from 635 US$/m^3 in 2012 to 560, and 543 US$/m^3 in 2030 for the multi-step and one-step (greenfield) approach, respectively. In this analysis, there is no difference between one-step expansion approach and the greenfield approach, as there are no ethanol production facilities using eucalyptus currently in Goiás. The capital costs of second generation industrial processing plants are the major element in the total ethanol production costs, even at large scale. Eucalyptus yield improvement is the main driver for the reduction in ethanol production costs in the multi-step approach.

The results depicted in Figure 5-7 show a significantly different cost breakdown for sugarcane and eucalyptus-based ethanol production. Despite the fact that second generation processing of ethanol has high industrial processing costs, the total ethanol production costs of eucalyptus processing are lower compared to sugarcane. This is due to the relatively high eucalyptus yield in Goiás, while sugarcane yield is moderate (compared to average Sao Paulo yield levels). Furthermore, due to selection of large scale industrial processing, the economies of scale are exploited for eucalyptus processing by the optimization model. For sugarcane processing also smaller industrial processing facilities are selected, as transport costs are more important for sugarcane.

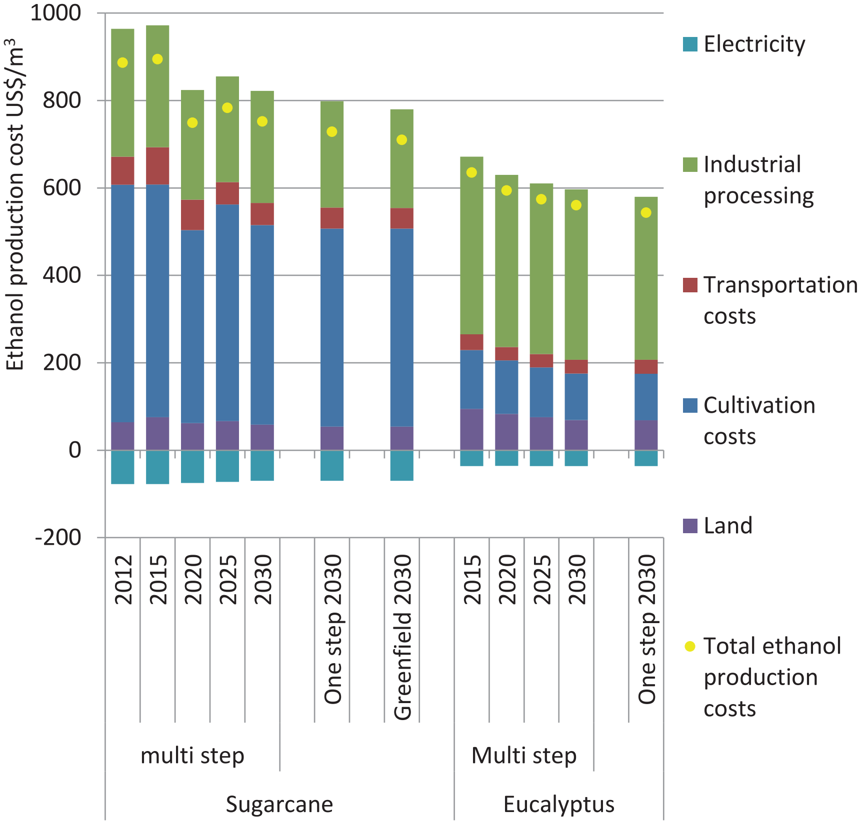

Figure 5-7 Average ethanol production cost breakdown utilizing sugarcane (left) and eucalyptus (right) in Goiás for multi-step, (2015, 2020, 2025 and 2030) one-step (2030) and greenfield optimisation (2030). Only the cultivation, transport and industrial processing costs of biomass supply regions connected to plants built after 2012 are included.

5.5.3 Economic ranking and GHG emission intensity of ethanol production.

Figure 5-8 and 5-9 show the ethanol production costs (blue points, left axis) and GHG emission intensity (red points, right axis) of ethanol production in 2030 in Goiás using sugarcane (Figure 5-8) and eucalyptus (Figure 5-9). The ethanol production costs are determined per biomass supply region and ranked according to the total ethanol production costs, from low to high. Also the average GHG emission intensity of all ethanol produced (green line) is shown, as well as the GHG emission intensity of a fossil fuel comparator (purple line)[20]. Figures 5-8 and 5-9 only include new biomass supply regions; in other words, only the expansion between 2012 and 2030 is shown. Both Figures present

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[20] The GHG emission intensity of the fossil fuel comparator (gasoline) is adjusted for the lower combustion energy of ethanol compared to fossil fuels, and expressed as kg CO_2/m^3 ethanol. This enables the direct comparison with GHG emissions of ethanol production.

the results of the one-step expansion approach; the two other approaches show a similar pattern, with small differences in the transport and industrial processing costs and GHG emissions (caused by different transport distances).

The cost ranking of ethanol production from sugarcane, as shown in Figure 5-8, shows a large variation between the lowest and highest production costs (634 - 1207 US$/m^3). This is predominantly caused by the variation of sugarcane yields among the biomass supply regions. The sugarcane yield impacts the land costs per tonne harvested biomass of the supply regions but mainly affects the cultivation costs in those regions. For the highest ethanol production costs, also the costs for transport and industrial processing are significant. The GHG emission intensity of the ethanol produced are mainly determined by the former land-use carbon stock. The GHG emissions caused by sugarcane cultivation, transport and processing account for between 148 and maximal 490 kg CO_2/m^3. Three main land uses are the basis for the three groups of emission intensities shown in Figure 5-8: former cropland (78% of all biomass supply regions in 2030), pasture land (20%) and forested land (2%). Conversion of agricultural land results in negative GHG emissions, ranging between -570 and -100 kg CO_2/m^3 ethanol, as the carbon stock of sugarcane plantation is higher compared to the carbon stock of agricultural land (however, no indirect land-use effects have been taken into account). Note that the supply regions with lower sugarcane yield, commonly on the right side of Figure 5-8, have larger negative GHG emissions compared to high biomass yield supply regions. This is due to the net carbon stock gain which is spread over a lower amount of biomass supply. The conversion of pastures results in modest GHG emissions, 205-880 kg CO_2/m^3 ethanol, and the conversion of forested land results in high GHG emissions, ranging between 3150-5780 kg CO_2/m^3 ethanol, and thus performs far worse than fossil gasoline. Due to high amounts of cropland being converted to sugarcane plantations, the average GHG emission intensity of ethanol produced in Goiás is -80 kg CO_2/m^3 ethanol in contrast to the fossil fuel competitor of 1800 kg CO_2/m^3 (EC European Commission, 2010).

The cost ranking of ethanol production from eucalyptus, shown in Figure 5-9, shows a low variation in ethanol production costs, as the yield variation is low and biomass yield plays a less dominant role in overall ethanol production costs for eucalyptus, as indicated by Figure 5-7. The impact of industrial scale on the industrial processing costs is high, but in this study the impact on the industrial processing costs is limited as only large scale industrial plants are selected. For eucalyptus processing, the capital costs of industrial processing are more important than biomass cultivation costs. The range of total ethanol production costs for second generation processing of eucalyptus is between 492 and 681 US$/m^3 ethanol, see Figure 5-9. The GHG emission intensity for eucalyptus processing shows two main groups of emission intensities: expansion on agricultural land and cropland (59% of all biomass supply regions in 2030) and the expansion on forested land (41%). The eucalyptus cultivation, transport and processing GHG emissions account for 148 to maximal 289 kg CO_2/m^3. The main difference in GHG emissions compared to sugarcane cultivation and processing is due to low transportation costs (high yield and low moisture content) and lower cultivation GHG emissions. High carbon stock of eucalyptus plantations compared to cropland or pasture combined with high ethanol yield result in high avoided GHG emissions of eucalyptus processing in the range of -3220 and 0 kg CO_2/m^3 ethanol. In contrast, the initial carbon stock of forested land causes high GHG emission intensities of ethanol produced from eucalyptus cultivation on former forested land ranging between 3100-5890 kg CO_2/m^3 ethanol, see Figure 5-9. Therefore, on average, the GHG emission intensity of ethanol production utilizing eucalyptus in Goiás is 1290 kg CO_2/m^3 ethanol, only about 30% lower than the fossil fuel comparator.

Comparing the ethanol production of the two different biomass feedstock in Goiás, the total ethanol production costs of sugarcane is more affected by the yield variation in the biomass supply regions than the ethanol production costs of eucalyptus. Sugarcane cultivation costs are relatively high as Goiás is on average less suitable for sugarcane cultivation. The expansion of eucalyptus cultivation is largely allocated to former forested land, this result in a higher GHG emission intensity compared to sugarcane, which is often allocated to agricultural land. Note that the location of biomass supply regions is determined by PLUC in advance of the utilization of the optimization model.

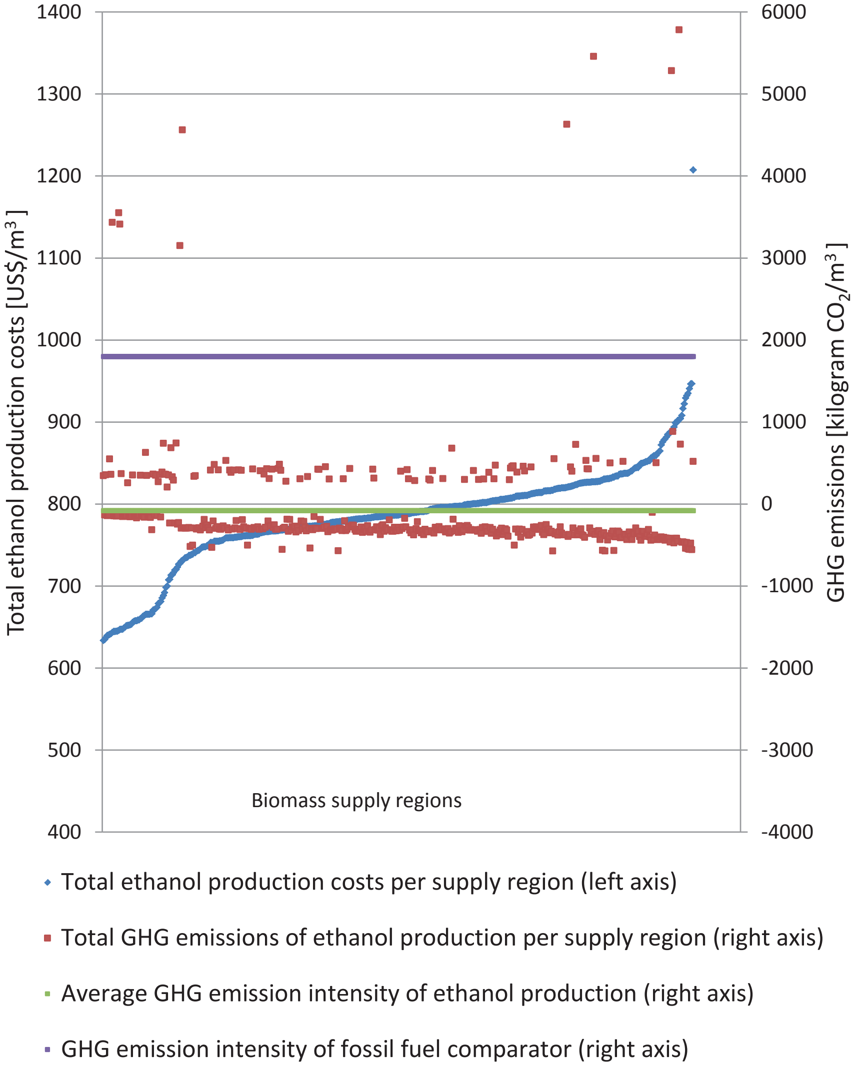

Figure 5-8 Costs supply curve of the total ethanol production costs (left y axis) of all biomass supply regions in Goiás (each one represented by one dot) delivering sugarcane, including their GHG emission intensity (right y axis), average GHG emission intensity (right axis) and the GHG emission intensity of the fossil fuel reference (right y axis).

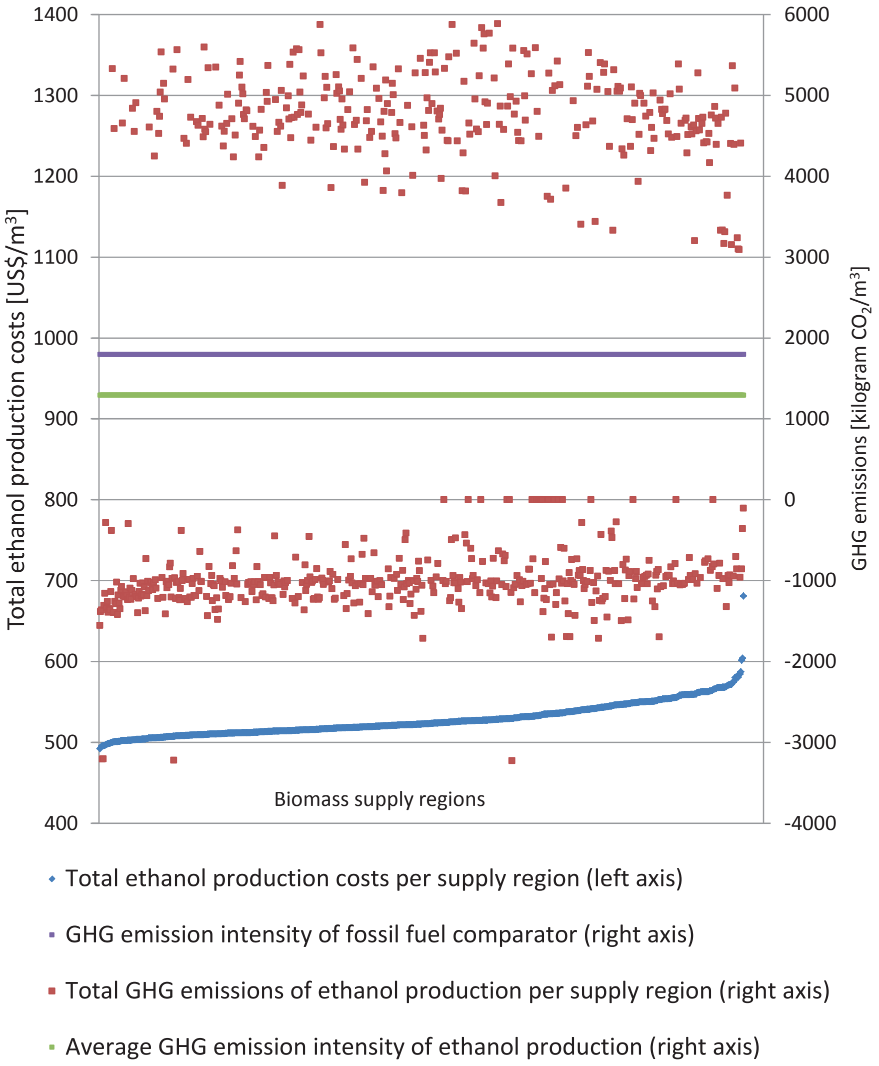

Figure 5-9 Costs supply curve of the total ethanol production costs (left y axis) of all biomass supply regions in Goiás delivering eucalyptus, including their GHG emission intensity (right y axis), average GHG emission intensity (right axis) and the GHG emission intensity of the fossil fuel reference (y right axis).

5.6 Discussion and conclusion

In this study, the optimization model BioScope is utilized to find the optimal location and scale of industrial plants based on an exogenously given distribution of biomass supply regions as provided by PLUC. The economic objective approach in the linear programming optimisation model is the driver for the selection of number and location of plants (reduce transport costs) and sizing (reduce capital costs) of industrial plants. The distribution of biomass supply regions is provided by the land use change model PLUC and is an important element in this optimization study. This novel approach, determining the land distribution in great detail with the land allocation model PLUC, plays a prominent role. The uncertainties of the PLUC model are discussed in (J. a. Verstegen et al., 2015). One key aspect when forecasting future land use with PLUC in relation to location-optimization is the *suitability* factor 'travel time to existing mills', as future sugarcane (and eucalyptus) supply regions will most likely deliver to a new industrial processing plants. The locations of future industrial mills are not embedded in PLUC, and therefore, this suitability factor has caused expansion of biomass supply regions in the vicinity of the existing industrial plants. For eucalyptus, PLUC does not include 'travel time to existing mills' as suitability factor. Using the predefined biomass supply regions, potential locations of new industrial processing plants, the transport distance between supply regions and processing plants, and the land use change emissions are also (indirectly) set by PLUC.

The agro-ecological suitability (spatially heterogeneous) and maximum yield value (time variable) jointly determine the biomass yield in the supply regions. The combination of the distribution of biomass supply regions and the varying yields of the supply regions is an important feature of this study and results in the spatial heterogeneous biomass availability. The potential regional variation in plantation management, and its impact on biomass yield, is not considered. However, as most plantations are managed for economic benefits, limited regional variation in plantation management is assumed. Information on spatially explicit sugar cane yield levels in Goiás was not available. Therefore, the maximum attainable biomass yield was based on the relative suitability of biomass supply regions and the total biomass production in Goiás in 2012. Biomass yield also has a strong influence on the biomass cultivation costs, especially for sugarcane cultivation. The variation in biomass supply and biomass cultivation costs is determined by the variation in agro-ecological suitability, as described in section 5.3.4.

For the processing of sugarcane, efficient first generation ethanol production in combination with highly-efficient cogeneration is considered, as this is currently the most cost-efficient technology available at commercial scale and already installed in Brazil (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014). For eucalyptus processing, a novel technology is considered, which is still in a research and development stage. To obtain ethanol yields at commercial scale as assumed in this analysis, large upfront investments are required for further development and commercialization of the second generation processing technology. Selecting a novel technology with low industrial processing costs resulted in low ethanol production costs, especially for 2015. Large scale processing is preferred in all expansion approaches, as both industrial processing technology experience economies of scale. The linear relationship between industrial scale and capital costs sets an initial fixed investment, this is mainly important at small scale. The linear relationship between scale and total investment costs for the two scale ranges, as based on (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014), have a data fit of 0.99. Therefore, small scale industrial processing is expensive, and transport of biomass to a large industrial plant is most of the times preferred over the construction of a small industrial plant. However, it is uncertain if the ethanol industry is willing to take the financial risk of these large investments. Furthermore, it is highly uncertain if these production cost levels can be met in 2030. Therefore, even though production costs for eucalyptus-based ethanol are projected to be significantly lower in 2030 compared to sugar-case based ethanol, these estimates are inherently more uncertain. Also, as Brazilian ethanol production is currently 100% sugarcane based, it is questionable whether industrial parties will be willing to invest in ethanol production based on eucalyptus. Nevertheless, as the land suitability of Goiás in general is in favour of eucalyptus, the anticipated lower costs combined with the advantages of year-round production (300 vs 170 days of operation) warrant further consideration to develop eucalyptus-based ethanol plants.

Only one preselection criterion is used to determine the potential industrial processing plant locations. In this study, industrial plants can only be planned in biomass supply regions. This preselection had to be considered to avoid long calculation time of the optimisation model. As current locations of existing industrial plants are in or in close proximity of biomass supply regions, this assumption is deemed appropriate for Goiás. Other preselection criteria, for example distance between existing mills and large cities (as a proxy for ethanol demand) or distance of the field to a nearby road, were not considered accurate.

The results show that large scale industrial processing is preferred due to clustered biomass supply, low transportation costs and economies of scale for industrial processing. In several cases, the maximum allowable scale as set in the optimization model, restricts the scale of industrial plants. Optimal locations differ among the different expansion approaches used, in most cases industrial plants are preferred in high yielding biomass supply regions to reduce average transportation costs. The differences in total ethanol production costs of sugarcane processing are 894 US$/m^3 ethanol in 2015 and decrease to 752, 715 and 710 US$/m^3 ethanol in 2030 for the multi-step, one-step and greenfield expansion respectively. For eucalyptus, the ethanol production costs decrease from 635 US$/m^3 in 2015 to 560, and 543 US$/m^3 in 2030 for the multi-step and one-step (greenfield) approach respectively. These costs differ only marginally for the different optimisation approaches in 2030 due to the utilization of the same biomass supply regions and the small variation in capital investment costs of industrial plants. By optimizing the ethanol production costs for the state of Goiás as region as a whole, the size and location of individual industrial processing plants may be suboptimal locally, but is part of the best overall solution. In reality, different mill owners would obviously aim to minimize ethanol production costs per plant. This situation somewhat resembles the multi-step approach. Compared to the multi-step-approach, the greenfield optimisation achieves about 6%

lower system-wide overall production costs for sugarcane, and about 3% lower costs for eucalyptus. Thus, under the preconditions used in this study, a system-wide optimisation has only a marginal impact on overall production costs. Furthermore, note that boundary effects may occur, as sugarcane and eucalyptus transport to and from industrial plants in neighbouring states is excluded in the current study, but it is difficult to determine how many industrial plants or biomass supply regions are affected due to this effect.

The utilisation of PLUC also enables the calculation of total GHG emission intensity of ethanol produced, including land-use change emissions. The calculation of the GHG emission intensity, especially the land-use change emissions, is often neglected in supply chain optimization studies. Due to the conversion of cropland, pasture or formerly forested land the direct carbon emissions or gains due to land-use change dominate the overall GHG emission intensity. However, the land use change emissions or total GHG emission intensity of ethanol was not incorporated in the land use change model or used as optimization objective. Therefore, this analysis shows only the potential GHG emission intensity when the land use distribution and the supply chain design are not optimized for GHG emissions. The GHG emission intensity of ethanol production using the economically optimal supply chain designs is dominated by the direct land use change emissions. It is important to note that only the direct land-use change emissions are taken into account, as this paper does not incorporate the indirect land use change dynamics due to the expansion of ethanol production, meaning that this approach is a strong simplification of the land use change emissions. Due to the predominant expansion of sugarcane cultivation on former cropland, while eucalyptus cultivation expands to a much larger extent on originally forested land, the average GHG emission intensity of sugarcane processing if far lower compared to eucalyptus processing. However, this is only true given the (exogenously determined) distribution of supply regions and does not consider any indirect land use change emissions. Thus, based on the results presented here, a conclusion that sugarcane-based ethanol produced in Goiás would in general have lower GHG emissions than eucalyptus cannot be drawn. In fact, compared to sugarcane, eucalyptus-based ethanol achieves higher direct savings when produced on former agricultural land. However, the results indicate that, due to the importance of land use change emissions, an optimisation on minimal overall GHG emissions could yield significant possibilities for GHG emission reductions. Such an analysis would also have to take into account indirect land use change effects, also in relation to other (agricultural) land uses and minimisation of supply chain GHG emissions, for example from agricultural inputs. In addition, future ethanol supply chain optimization models could also include a multi-objective optimization procedure to better quantify and optimize the trade-off between GHG emissions and economic performance. In other words; next to the improvement potential addressed in this study, more improvement measures or trade-offs can be quantified in future optimization studies.

Acronyms and definitions

Abbreviations

Bioscope	Decision support system using a MILP structure, developed by University Illinois
CPLEX	A GAMS solver designed to solve large, difficult problems with minimal user intervention.
CSP	centralized storage and pre-processing
DSS	Decision support system
GAMS	General Algebraic Modelling System
GHG	Greenhouse gas
GIS	geographical information system
LP	Linear programming
MILP	mixed integer linear programming
SC	Supply chain
TC	tonne cane

Nomenclature

Indices

i	biomass supply region
k	industrial processing facility location

Acknowledgements

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Supplementary information

5-SI-1Map of sugarcane cultivation areas in Goiás.

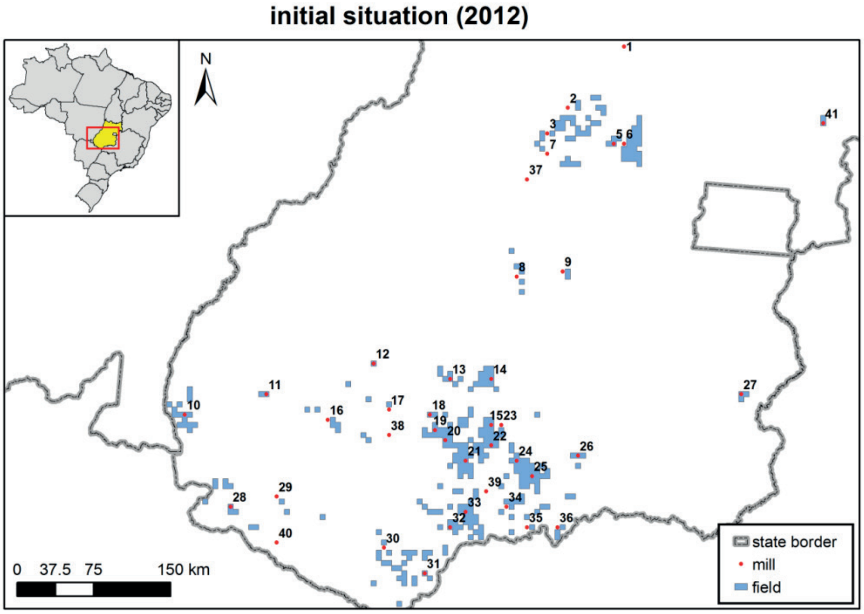
initial situation (2012)

Figure 5-SI-1, Map of Goiás with sugarcane cultivation fields and sugarcane processing mills.

5- SI-2 Sugarcane processing facilities in Goiás.

Table SI-1 Overview of sugarcane processing facilities in Goiás, numbers in left column correspond to the map in SI-1.

#	Name	Municipality	Road	Capacity	Ethanol Mil L. 2009	Status 2011	Coordinates (manually checked)^{E}
				tonne/year			
1	URUAÇU AÇÚCAR E ÁLCOOL LTDA^{A}	URUAÇU^{A}	Estrada UR-4, s/n – km 13^{A}	unknown	22000	Operation suspended ^{B}	-14.416306, -49.065513 (9.8 km)
2	VALE VERDE EMPREENDIMENTOS AGRÍCOLAS LTDA^{A}	ITAPACIA^{A}	Rodovia GO 336 – km 14^{A}	1 506 000^{C}	135000	In operation ^{B}	-14.979458, -49.537791 (right next to Go 336)
3	COOPERATIVA AGROINDUSTRIAL DE RUBIATABA LTDA^{A}	RUBIATABA^{A}	Rodovia GO 434 – km 24^{A}	Unknown	110000	In operation ^{B}	15º10'42''S 49º45'29''W^{H} (600 m of GO 434)
4	JALLES MACHADO S/A - UNIDADE OTÁVIO LAGE^{A}	GOIANÉSIA^{A}	Rodovia GO 338 – km 33 à esquerda, km 3^{A}	550 000 ^{C}	-	In operation ^{B}	Not found
5	USINA GOIANÉSIA S/A^{A}	GOIANÉSIA^{A}	Rod. GO 438 – km 12^{A}	968 000 ^{C}	-	In operation ^{B}	15º12'51''S 49º05'53''W^{H} (600 m of GO 438)
6	JALLES MACHADO S/A^{A}	GOIANÉSIA^{A}	Rodovia GO 080 – km 71.5^{A}	2 600 000 ^{C}	98596	In operation ^{B}	15º13'01''S 48º59'18''W^{H} (right next to GO 080)
7	CRV INDUSTRIAL LTDA^{A}	CARMO DO RIO VERDE^{A}	Rodovia Carmo do Rio Verde/Rubiataba – km 2,5^{A}	Unknown	48600	In operation ^{B}	15º20'45''S 49º43'44''W^{H} (Right next to GO 334)
8	ANICUNS S/A	ANICUNS^{A}	Rodovia	1728000 ^{C}	64000	In	-16.415926, -49.947678

	ÁLCOOL E DERIVADOS[A]		Anicuns/Americano do Brasil – km 06[A]			operation [B]	(Next to Go 156)
9	CENTROÁLCOOL S/A – CENASA[A]	INHUMAS[A]	Rodovia Inhumas/Anápolis – km 03[A]	792 000 [C]	86000	In operation [B]	-16.347405, -49.484247 (Next to Go 222)
10	BRENCO – USINA MORRO VERMELHO - ODEBRECHT AGROINDUSTRIAL[A]	MINEIROS[A]	Rod. GO 341 – km 68, Faz. Morro Vermelho[A]	2 780 000 [C]	77151	In operation [B]	-17.760174, -53.027400 (photo) (9,4 km to GO 341)
11	BRENCO – USINA PEROLÂNDIA-ODEBRECHT AGROINDUSTRIAL[A]	PEROLÂNDIA[A]	Rodovia BR 364, km 256, s/n – Z. Rural[A]	Unknown (around 300 000) [D]	-	Operational as of 2012 [B]	-17.536552, -52.257520 (8.5 km to GO-516)
12	USINA SERRA DO CAIAPÓ S.A[A]	MONTIVIDIU[A]	Rod. GO 174 – km 62 – Fazenda Lago Azul[A]	550 000 [C]	42615	In operation [B]	-17.312032, -51.220984 (4,9 km to GO 174)
13	USINA NOVA GÁLIA LTDA[A]	PARAÚNA[A]	Rod. GO 333 – Sentido Rio Verde - Jandaia – Z. Rural[A]	750 000 [C]	50000	In operation [B]	-17.332448, -50.494890 (6,1 km to Go-333)
14	DENUSA – DESTILARIA NOVA UNIÃO S/A[A]	JANDAIA[A]	Margem Esquerda da Rodovia BR 060 – km 274[A]	1 220 000 [C]	119680	In operation [B]	17º16'41"S 50º08'57"W[H] (7,4 km to GO-164)
15	TROPICAL BIOENERGIA S/A[A]	EDÉIA[A]	Rodovia Takayuki Maeda (GO 410) – km 51	2 400 000 [C]	101008	In operation [B]	-17.681391,-50.117605 (photo) (Next to GO-410)

			Zona Rural[A]				
16	COSAN CENTROESTE S/A AÇÚCAR E ÁLCOOL[A]	JATAÍ[A]	Rodovia GO 406 – km 25 à direita 6 km – Faz. StºAntônio do Rio Doce[A]	Unknown	55710	In operation [B]	-17.695388, -51.622078 (5 km to GO-184)
17	USINA RIO VERDE LTDA (DECAL) [A]	RIO VERDE[A]	Rodovia GO 174, km 32 – Faz. Alvorada[A]	Unknown	45200	In operation [B]	17°32'47.1"S,51°04'36.0"W [H] (2.1 km to GO-174)
18	FLORESTA S/A AÇÚCAR E ÁLCOOL[A]	SANTO ANTÔNIO DA BARRA[A]	Rodovia BR 060, km 351, Fazenda Floresta, Z. Rural[A]	1200000 [C]	50000	In operation [B]	-17.616769, -50.714598 (2,2 km to [060])
19	CAMBUÍ AÇÚCAR E ÁLCOOL LTDA[A]	SANTA HELENA DE GOIÁS[A]	Rodovia BR 452, km 33, Fazenda San Carlos, Z. Rural[A]	Unknown (2 000 000 in 2014) [D]		Operational in 2012 [B]	-17.925150, -50.634710 (under construction) (2.1 km to Go 452)
20	USINA SANTA HELENA DE AÇÚCAR E ÁLCOOL S/A[A]	SANTA HELENA DE GOIÁS[A]	Rod. Mun. Turvelândia, GO 210, km 06[A]	2 100 000 [C]	44394	In operation [B]	17º49'15''S 50º32'19''W[H] (400m to Go-210)
21	VALE DO VERDÃO S/A AÇÚCAR E ÁLCOOL[A]	TURVELÂNDIA[A]	Rod. GO 409 – km 2 – Fazenda Baessa[A]	3 611 000 [C]	185000	In operation [B]	17º58'03''S 50º19'01''W[H] (1.2 km to GO-409)
22	USINA SÃO PAULO ENERGIA E ETANOL S/A[A]	PORTEIRÃO[A]	Rodovia GO 210 – km 98 – Zona Rural[A]	900 000 [C]	80000	In operation [B]	-17.841041, -50.070413 (700 m to GO-210)
23	CAÇU COMÉRCIO E IND. DE AÇÚCAR E ÁLCOOL LTDA[A]	VICENTINÓPOLIS[A]	Rod. Mun. Vicentinópolis/Porteirão, km 10[A]	1000 000 [C]	41000	In operation [B]	-17.689820, -49.987035 (11km to GO-410)

24	BOM SUCESSO AGROINDÚSTRIA LTDA[A]	GOIATUBA[A]	Rod. GO 210 – km 335,1 – Zona Rural[A]	646 000 [C]	-	In operation [B]	No actual site: photo placement matches site - 17.952008, -49.853640 (700m to GO-210)
25	GOIÁSA – GOIATUBA ÁLCOOL LTDA[A]	GOIATUBA[A]	Rodovia GO 040 – km 194 – Acesso 7 km à direita[A]	2 629 000 [C]	135841	In operation [B]	18º04'16''S 49º40'23''W[H] (6.5 km to GO-040)
26	CEM – CENTRAL ENERGÉTICA MORRINHOS S/A[A]	MORRINHOS[A]	Rod. BR 153 – km 646 – Faz. Samambaia[A]	876 000 [C]	-	In operation [B]	-17.927993, -49.234294[I] (900m to [153])
27	LASA – LAGO AZUL S/A[A]	IPAMERI[A]	BR 050 – km 154- Fazenda Lago Azul[A]	500 000 [C]	30000	In operation [B]	-17.256829, -47.689460 (4.2 km to GO-020)
28	CERRADINHO BIOENERGIA S/A[A]	CHAPADÃO DO CÉU[A]	Rod. GO 050 – km 11 + 950 mts – Faz. Âncora – Z.Rural[A]	2840 000 [C]	144000	In operation [B]	-18.469336, -52.602286 (900m to GO-050)
29	ENERGÉTICA SERRANÓPOLIS LTDA[A]	SERRANÓPOLIS[A]	Rodovia GO 184 – km 65 – Fazenda Bonito[A]	850 000 [C]	73170	In Operation [B]	-18.384230, -52.106169 (6,8 km to GO-184)
30	RIO CLARO AGROINDUSTRIAL S/A- ODEBRECHT AGROINDUSTRIAL[A]	CAÇÚ[A]	Fazenda Santo Antônio – s/n – Zona Rural[A]	2 650 000 [C]	98000	In operation [B]	-18.792796, -51.003885 (on google maps under construction) (1.74 km to GO-174)
31	ENERGÉTICA SÃO SIMÃO S/A[A]	SÃO SIMÃO[A]	Fazenda Pateiro – Rodovia GO 164 – km 02 – Z.Rural[A]	Unknown	36000	Temporarily out of operation [B]	-18.971689, -50.635022 (next to GO-164)
32	USINA BOA VISTA S/A[A]	QUIRINÓPOLIS[A]	Rod. GO 164, km 1 – Z. Rural[A]	2 000 000 [C]	195306	In operation [B]	-18.548619, -50.435990 (next to [483])

33	SJC BIOENERGIA S/A - USINA SÃO FRANCISCO[A]	QUIRINÓPOLIS[A]	Rod. GO 206 – km 18 – Fazenda São Francisco[C]	4 725 000 [C]	131001	In operation [B]	-18.431508, -50.261846 (In google maps under construction) (2.8 km tot GO206 / [483])
34	USINA PANORAMA S/A[A]	ITUMBIARA[A]	Rodovia BR 452, km 60, Fazenda Boa Sorte, Z. Rural[A]	2 090 000 [C]	93798	In operation [B]	-18.339020, -49.865006 (8.1 km to GO-040)
35	SJC BIOENERGIA S/A - USINA CACHOEIRA DOURADA[A]	CACHOEIRA DOURADA[A]	Rodovia GO 206, km 25, esquerda 1,5 km[A]	Unknown	-	Operational as of 2013 [B]	-18.505795, -49.652695 (1.6 km to GO-206 / [483])
36	CENTRAL ITUMBIARA DE BIOENERGIA E ALIMENTOS S/A[A]	ITUMBIARA[A]	Estrada Municipal Itumbiara/Cachoeira Dourada[A]	1 758 000 [C]	67326	In operation [B]	-18.517563, -49.361569 (9.5 km to GO-206 / [483])
37	VALE VERDE EMPREENDIMENTOS AGRÍCOLAS LTDA[A]	ITAPURANGA[A]	Rodovia GO 156, km 55, Zona Rural[A]	520 000 [C]	23496	Temporarily out of operation [B]	-15.582671, -49.884995 (right next to GO156)
38	RIO VERDE INDÚSTRIA DE AÇÚCAR E ÁLCOOL LTDA. [A]	RIO VERDE[A]	RODOVIA GO174 – km 18[A]	Unknown	-	Operational as of 2013 [B]	-17.829036, -50.978375[J] (Next to [060])
39	SMBJ Agroindustrial	Bom Jesus de Goiás	Unknown	Unknown	-	Operational as of 2014 [B]	Unknown;
40	Nardini[F]	Apore[F]	Fazenda Santa Lucia - Rod. GO	Unknown	-	Operational as of	Unknown; approximately --18.682629, -52.073692

			184 km 131[F]			2013 [B]	(next to GO-184)
41	CBB – Bioenergética[G]	VILA BOA[G]	Unknown	Unknown	30780	Unknown	-14.864930, -47.137616 (17.5 km to [020])

[A] RELAÇÃO DAS UNIDADES PRODUTORAS DE ETANOL E AÇÚCAR DO ESTADO DE GOIÁS, ASSOCIADAS AO SIFAEG.

[B] Plants operational status found in http://www.seplan.go.gov.br/sepin/pub/Godados/2011/07-comercio/07-tab12.htm

[C] Annuario da Cana, Brazilian Sugar and Ethanol Guide, 17th edition, 2011

[D] news items on the internet

[E] using google maps satellite images

[F] company website on production site see: http://www.nardini.ind.br/pt/apore

[G] using available information of ministry of agriculture http://www.agricultura.gov.br/arq_editor/file/Desenvolvimento_Sustentavel/Agroenergia/Orientacoes_Tecnicas/Usinas%20e%20Destilarias%20Cadastradas/Relacao%20de%20cadastradas%2030-09-2013.pdf

[H] using coordinates as specified by database on cogeneration: http://www.datacogen.com.br/datacogen/empr_gerais.asp?id_cogen=321

[I] Location also verified by: http://wikimapia.org/#lang=en&lat=-17.927374&lon=-49.199610&z=14&m=b&show=/18592843/pt/CEM-Central-Energética-Morrinhos

[J] http://www.grupoandrade.com.br/unidade2.php

5-SI-3 Costs parameters

Table SI-2 Cost parameters for sugarcane and eucalyptus cultivation.

	Sugarcane cultivation	Eucalyptus cultivation
Machine	456.68	186.04
Machine operation labour	84.70	44.81
Diesel	405.15	40.74
Manual labour	0.0	-
Machine maintenance	49.70	8.56
Lubricants	5.15	0.94
Un-skilled labour	14.42	-
Other labour	0.67	69.54
Agrochemicals	290.12	71.47
Seedlings	166.84	28.37
Subtotal (a)	**1432 US$/ha**	**450.47 US$/ha**
Machine	3.47	1.948
Machine operation labour	0.48	0.427
Diesel	2.98	0.469
Machine maintenance	0.32	0.0896
Lubrificants	0.00	0.00986
N-fertilizer	1.94	3.65
P-fertilizer	1.49	-
K-fertilizer	4.02	-
Subtotal (b)	**17.66 US$/tonne cane**	**6.593 US$/dry tonne**
Administrative cost (c)	**6%**	**6%**

Table SI-3 GHG emission data cultivation of sugarcane

	Unit	**Value**	**Emission factor [kg CO$_2$/quantity]**
Diesel use machinery	L/ha-year	35.5[A]	3.14[B]
	L/tonne	1.552[C]	
N-fertilizers	kg N/tonne sugarcane	0.777[D]	3.97 – 0.083[E]
P-fertilizers	kg P/tonne sugarcane	0.249[D]	1.3[E]
K-fertilizers	kg K/tonne sugarcane	0.98[D]	0.71[E]
Limestone	kg limestone/ha	2000[F]	0.01 – 0.477[G]
Herbicides	kg herbicides/ha	2.2[H]	25[I]
Insecticides	kg insecticides/ha	0.16[H]	29[I]
Trash decay	kg trash/tonne sugarcane	140[J]	0.028[K]
Filtercake	kg/tonne sugarcane	7[L]	0.071[M]

application			
Vinasse application	L vinasse/tonne sugarcane	880[N]	0.002[U]

[A] Diesel consumption machinery, other than harvest equipment. The diesel consumption is specified by (Macedo, Seabra, & Silva, 2008) as 312.3 L/ha at planting and 9.1 L/ha at ratoon.

[B] Emissions factor of diesel in Brazilian transport is based on the GHG intensity of diesel production and consumption 24.1 gram C/MJ diesel (Macedo et al., 2008) and Higher Heating Value of diesel of 44MJ/l, as specified by (Hamelinck, Hooijdonk, & Faaij, 2005).

[C] The diesel consumption of total harvesting is specified by (Macedo et al., 2008) as 1.55 L/tonne sugarcane.

[D] Fertilizer input for sugarcane has been expressed by (Seabra, Macedo, Chum, Faroni, & Sarto, 2011) as 777 gram N/tonne cane, 249 gram P_2O_5/tonne and 980 gram K_2O.

[E] The GHG emission intensity of fertilizers is specified by (Macedo et al., 2008) as 3.97 kgCO_2/kg N-fertilizer, 1.30 kgCO_2/kg P-fertilizer and kgCO_2/kg K-fertilizer. Carbon dioxide equivalent emissions of N_2O emissions are expressed as 0.477 kgCO_2/kg N-fertilizer, see (Macedo et al., 2008) for the details.

[F] Lime application is 2 tonne per hectare as specified by (Macedo et al., 2008).

[G] GHG emissions of limestone application are twofold, first the emissions of production are 0.01 kg CO_2/kg limestone, while the N_2O emissions are recalculated to 0.477 kgCO_2/kg limestone (Macedo et al., 2008).

[H] Active ingredients of herbicides used in sugarcane cultivation are expressed as 2.2 kg/ha, while the use of insecticides are 0.116 kg/ha (Macedo et al., 2008).

[I] The GHG emission factor is 25 and 29 kg CO_2/kg active ingredient respectively (Macedo et al., 2008).

[J] Amount of sugarcane trash left in the field after harvest is approximately 140 kg trash per tonne sugarcane stalks (Dias et al., 2011).

[K] GHG emission factor of unburned trash left in the field is expressed as 28 kgCO_{2eq}/kg trash (Macedo et al., 2008).

[L] Filtercake production is approximately 6 to 8 kg per tonne sugarcane (Macedo et al., 2008), a value of 7 kg/tonne cane is considered in this analysis.

[M] The GHG emission factor is 71 kg CO_2/kg filtercake mud (Macedo et al., 2008).

[N] Vinasse production is approximately 10 -15 L/L ethanol. Using an average ethanol production of 80 L ethanol/tonne cane, vinasse production is considered to be 880 L vinasse/tonne cane.

[O] The GHG emission factor is 2 g CO_2/L vinasse (Macedo et al., 2008)

Table SI-4 GHG emission data of eucalyptus cultivation

	Unit	**Value**	**Emission factor [kg CO_2/quantity]**
Diesel use machinery	L/ha-year	6.72[A]	3.14[B]
	L/tonne	2.464[C]	
N-fertilizers	kg N/tonne eucalyptus	0.667[D]	3.97 – 0.083[E]

P-fertilizers	kg P/tonne eucalyptus	0.654[D]	1.3[E]
K-fertilizers	kg K/tonne eucalyptus	1.7[D]	0.71[E]
Limestone	kg limestone/ha	2500[F]	0.01 – 0.477[G]
Herbicides	kg herbicides/ha	2.37[H]	25[I]
Forestry residue	kg residue/tonne eucalyptus	150[J]	0.028[K]

[A] Diesel consumption machinery, other than harvest equipment. The diesel consumption of forestry plantation management as specified by (Markewitz, 2006) as 168 L/ha over a planting period of 25 year.

[B] Emissions factor of diesel in Brazilian transport is based on the GHG intensity of diesel production and consumption 24.1 gram C/MJ diesel (Macedo et al., 2008) and Higher Heating Value of diesel of 44MJ/l, as specified by Hamelinck 2005]

[C] The diesel consumption of harvesting equipment as specified by (Markewitz, 2006) as 616 L/ha.

[D] Fertilizer input for eucalyptus has been expressed by (Couto, 2013) as 82 kg N, 90 kg P and 160 kg K in the first rotation and 64 kg N and 142 kg K in the second and third rotation.

[E] The GHG emission intensity of fertilizers is specified by (Macedo et al., 2008) as 3.97 $kgCO_2$/kg N-fertilizer, 1.30 $kgCO_2$/kg P-fertilizer and $kgCO_2$/kg K-fertilizer. Carbon dioxide equivalent emissions of N_2O emissions are expressed as 0.477 $kgCO_2$/kg N-fertilizer, see (Macedo et al., 2008) for the details.

[F] Lime application is 2500 kg per hectare as specified by (Couto, 2013).

[G] GHG emissions of limestone application are twofold, first the emissions of production are 0.01 kg CO_2/kg limestone, while the N_2O emissions are recalculated to 0.477 $kgCO_2$/kg limestone (Macedo et al., 2008).

[H] Active ingredients of herbicides used in sugarcane cultivation are expressed as 2.37 kg/ha (Couto, 2013)

[I] The GHG emission factor is 25 and 29 kg CO_2/kg active ingredient respectively (Macedo et al., 2008).

[J] Amount of residues left in the field are estimated as 15% residues left in the forest plantation, based on (Jonker, Junginger, & Faaij, 2014)

[K] GHG emission factor of residues left in the field is expressed as 28 $kgCO_{2eq}$/kg trash (Macedo et al., 2008).

Chapter 6

Economic performance and GHG emission intensity of sugarcane and eucalyptus derived biofuels and biobased chemicals in Brazil

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Abstract

Biomass feedstock can be used for the production of biofuels or biobased chemicals to reduce anthropogenic GHG emissions. Earlier studies about the techno-economic performance of biofuel or biobased chemical production vary in biomass feedstock, conversion process and other techno-economic assumptions. This makes a fair comparison between different industrial processing pathways difficult. The aim of this study is to uniformly quantify the factory gate production costs and GHG emission intensity of biobased ethanol, ethylene, 1,3 propanediol and succinic acid, and compares these to each other and their respective fossil equivalent products. Brazilian sugarcane and eucalyptus are used as biomass feedstock in this study. A uniform approach is applied to determine the production costs and GHG emission intensity of biobased products, taking into account feedstock supply, biobased product yield, capital investment, energy, labour, maintenance and processing inputs. Due to the uncertainty associated with the parameter used for biobased product yield, feedstock cost and GHG emissions, fixed capital investment, industrial scale, and energy costs and GHG emissions the results are presented in ranges rather than points. The range of biobased product production costs with a 60% confidence interval are 0.64 – 1.10 US$/kg ethanol, 1.18 – 2.05 US$/kg ethylene, 1.37 – 2.40 US$/kg 1,3 PDO and 1.91 – 2.57 US$/kg succinic acid. The cost ranges of all biobased products partly or completely overlap with the range of the production costs of the fossil equivalent products. The results shows that sugarcane based 1,3 PDO and to a lesser extent the production of succinic acid have the highest potential benefit. The GHG emission reduction is 1.28 – 2.17, 3.56 – 4.11, 2.38 – 5.19 and 0.15 – 4.25 kg CO_2/kg biobased product for ethanol, ethylene, 1,3 PDO and succinic acid respectively. Considering the potential GHG emission reduction and potential profit per hectare, the pathways utilizing sugarcane score better than eucalyptus feedstock due to the high yield of sugarcane specifically in Brazil. Overall, it was not possible to choose a clear winner, as a) the best-performing biobased product strongly depend on the chosen metric, and b) the large ranges found, especially for PDO and succinic acid, independent of the chosen metric. To quantify the performance better, more data is required regarding the biobased product yield, equipment costs and energy consumption of biobased industrial pathways, but also about the production costs and GHG emission intensity of fossil equivalent products.

6.1 Introduction

To limit climate change and its impact on natural and human systems, *substantial and sustained* reductions in GHG emissions are required (IPCC, 2014b). The use of biomass for the production of bioenergy and biobased products is often highlighted as an effective way to reduce the GHG emissions (Bozell and Petersen 2010; Chum et al. 2011; GEA 2012; IEA 2015). Several Integrated assessment studies (i.a. Daioglou et al. 2014, 2015; Popp et al. 2014; Selosse and Ricci 2014), have shown an increasing employment of bioenergy and biobased products in the future to reduce GHG emissions. The potential GHG emission reduction by biomass employment is influenced by the (biophysical) limits of biomass supply and the techno-economic performance of biobased supply chains (Popp et al., 2014). As indicated by the review of Creutzig et al. (2015), the sustainable technical biomass supply potential is limited to 100-300 EJ/year, this value reached medium agreement among scientists; biomass supply potential above 300 EJ/year has a low agreement among scientists. Given the restricted biomass supply, it is important to utilize the biomass in such a manner that high amounts of GHG emissions are avoided, while at the same time the biobased products are able to compete economically with their respective fossil reference products. Therefore, more insight in the production costs and GHG emission intensity of biobased products is required.

Studies highlighting the potential utilization of biomass for the production of biofuel and biobased chemicals are plentiful, among others (Bozell and Petersen 2010; Gerssen-Gondelach et al. 2014; Harmsen, et al 2014; Taylor et al. 2015;, Werpy, and Petersen 2004). However, studies quantifying the economic performance of biobased products in detail, generally focus on a single biobased product via one major industrial pathway (Efe, van der Wielen, & Straathof, 2013; Nitzsche, Budzinski, & Gröngröft, 2016; Orjuela, Orjuela, Lira, & Miller, 2013; J. A. Posada, Brentner, Ramirez, & Patel, 2016; J. A. Posada & Cardona, 2012; J. Posada, Cardona, Higuita, Tamayo, & Pisarenko, 2013) or one biobased product via different industrial pathways (e.g. Dias, et al. 2011; Haro, et al 2013; J.G.G. Jonker, et al 2014; Koutinas et al. 2016). The main conclusion of these studies is that the main elements of the production costs are the expenses for feedstock, energy consumption (or in some cases energy surplus), capital investment, and maintenance costs. Studies comparing different biobased products are scarce, Gargalo, et al. (2016) being one of the few exceptions. However, that study lacks a sufficient level of detail about capital investment and energy use to enable a detailed bottom-up assessment. Furthermore, the quantification of the GHG emission intensity of the biobased products is generally neglected in the studies mentioned above. Also, these studies vary in feedstock (composition), industrial scale, energy price, and economic assumptions related to e.g. maintenance, annuity, and labour. In consequence, no uniform comparison of the economic performance and GHG emission intensity of different industrial processing pathways of biomass for energy or materials was found in literature. To enable a fair comparison of the costs and GHG intensity of different biobased production pathways (with different feedstock), the use of uniform economic assumptions and a comparable unit of analysis is required.

In summary, the use of biomass for the production of biofuels and biobased chemicals faces two major challenges in the future. The first challenge is to achieve high GHG emission reductions given the limited available land for biomass cultivation. Secondly, the production costs of a biobased production pathway should be able to compete with their respective fossil reference product, as well as compete with other biobased production pathways. To enable a fair comparison between different industrial processing pathways, a uniform approach should be applied to assess the economic performance and GHG emission intensity of different biobased products. Therefore, the objective of this study is to quantify and compare the production costs and GHG emission intensity of four relevant biobased chemicals using different biomass feedstocks, and compare these to their fossil reference product. The present study differs from prior studies as it quantifies both the production costs and GHG emission intensity of different biobased products using an uniform approach. The factory gate production costs and GHG emission intensities are compared to their respective fossil reference. Furthermore, the economic viability and GHG emission reduction potential are compared among the different biobased production pathways. In order to do so, the potential profit and GHG emission reduction are expressed per hectare of biomass feedstock production. Because the economic performance and net avoided GHG emissions of biobased chemicals depend on various uncertain factors, this study pays explicit and structural attention to uncertainty by means of a Monte Carlo analysis. Also, a sensitivity analysis is performed. These analyses are performed to quantify the impact of the variation and uncertainty of the main economic and GHG emission parameters on the production costs and GHG emission intensity. The focus of this study is on the up- and midstream part of the processing (cultivation, transport and conversion), as the downstream processing of biobased products (distribution) is likely to be similar to the downstream processing of petrochemical platform products (An, et al 2011). As the economic and GHG emission parameters are region specific, this study focus on one particular geographical region. Brazil has been selected as a case study country because of the long standing history in ethanol production, the expected expansion of biomass production and the potential for the production of more advanced biobased supply chains.

The article is structured as follows. The selection of biomass feedstocks and biobased chemicals is described in section 6.2. The approach to calculate the economic performance GHG emission intensity is described in section 6.3. Input data for the quantification of the production costs and GHG emission intensity and the variation and uncertainty therein are given in section 6.4. The results are presented in section 6.5. Finally, discussion and conclusions are discussed in section 6.6 and 6.7 respectively.

6.2 Biomass feedstock description and biobased chemicals selection.

6.2.1 Biomass feedstock selection

Brazil has long standing history in the production of first generation ethanol production from sugarcane and it is currently the second largest bioethanol producer in the world (Chum et al. 2013). The harvest season 2015/2016 yielded a total of 605 Mtonne sugarcane for the production of sugar and ethanol (UNICA, 2017) on approximately 9 Mha (CONAB, 2015). Furthermore, Brazil has a large potential to expand the sugarcane cultivation area which is expected to increase an 6.4 Mha by 2021 (Goldemberg et al., 2014). The high sugarcane yield, high industrial conversion efficiencies and the co-production of electricity in the first generation ethanol industry in Brazil has resulted in large GHG emission reductions by gasoline substitution (J. Seabra et al., 2011; Ioannis Tsiropoulos et al., 2014).

The co-production of electricity is based on the utilization of bagasse (the left-over of sugarcane stalks after sugar extraction). Sugarcane bagasse can also be used in a second generation process to increase the ethanol yield per tonne sugarcane. However, this additional ethanol yield requires additional investments and reduces the electricity surplus (Dias, et al. 2011). In 2015, two industrial ethanol processing plants (designed for the production of 82 and 42 million litres ethanol per year) started operation in Brazil using sugarcane straw and bagasse (Kristin Seyboth et al., 2016). The development and commercialization of second generation industrial processing may also enable the use of eucalyptus as feedstock for ethanol production. Currently, approximately 5.6 Mha of eucalyptus is planted (IBÁ, 2016), mainly for the production of charcoal, pulp fibre, but also bioenergy (Laércio Couto, 2011). The development of second generation processing, especially the extraction and hydrolysis of sugars can also be beneficial for the production of other sugar derived products, such as succinic acid, polyethylene or lactic acid (Choi, Song, Shin, & Lee, 2015).

Sugarcane and eucalyptus biomass will be considered as the two biomass feedstock for industrial processing in this paper.

6.2.2 Biobased chemical selection

Sugarcane and eucalyptus can be used for the production of a wide variety of biofuels and biobased chemicals via biochemical or thermochemical industrial processing options. According to Gerssen-Gondelach et al. (2014), the fermentation of sugars provide an attractive technology for the production of biobased fuels and chemicals at present and on the longer term. Therefore, the biobased products selected for more detailed analysis are the output of a fermentation process (after sugar extraction). As there is a large range of potential biobased products that can be produced via fermentation, multiple selection criteria have been applied to support the selection of relevant biobased production pathways. In this study we use the following four selection criteria:

1. The biobased product has a current or future market size of at least 100 ktonne per year to make a potentially substantial contribution to GHG emission reduction. As biomass use for energy and materials is considered as an important GHG mitigation option, the production of the selected biobased chemicals should contribute to overall GHG emission reduction.
2. The biobased product can replace a fossil reference, either by direct or indirect substitution. In order to quantify the GHG emission reduction potential the biobased product should have a petrochemical reference product with a known GHG emission intensity.
3. The biobased product has received sufficient attention in literature and sufficient data is available to enable the analysis of the economic performance and GHG emission intensity.
4. The biobased product is the main output of the industrial processing pathway, to enable a direct comparison to a fossil reference product. Therefore, the common biobased production pathways is considered.

Table 6-1 provides an overview of biobased platform chemicals and their respective qualitative and quantitative scoring to the abovementioned criteria.

Table 6-1, Overview of potential biobased products with qualitative and quantitative scoring according to the selection criteria.

Chemical	Market potential	Fossil reference	Data availability	Biobased production route
Ethylene[A]	**127 Mtonne/y[1]**	**Ethylene (naptha)**	**++**	**Fermentation, followed by dehydration of ethanol to ethylene**
Ethanol[B]	**77 Mtonne/y**	**Gasoline (oil)**	**+++**	**Direct fermentation**
Propylene[C]	53 Mtonne/y[1]	Propylene (byproduct of petrochemical processing)	-	Various options, including fermentation
Butadiene	11 Mtonne[3]	Petrochemical 1,3-butadiene	-	Via ethanol or via direct fermentation[3]
Acetone[D]	3 Mtonne/y[1]	Acetone (coproduct of phenol production)	+/-	Co-product of ABE fermentation[4]
Adipic acid[E]	2.6 Mtonne/y[1]	Petrochemical Adipic acid	--	Various pathways, for example the fermentation of glucose[1]
Isopropanol[F]	2.3 Mtonne/y[1]	Via propylene	-	Fermentation[1]
n-Butanol	2.3 Mtonne/y[3]	n-butanol from mineral oil[3]	+	Co-product ABE fermentation[6]
Succinic acid[G]	**600 ktonne/y[1]**	**Succinic acid / Maleic Anhydride**	**+/-**	**Fermentation[3]**
Lactic acid[H]	472 ktonne/y[6]	No direct; Lactic acid can produce different polymers.	+/-	Direct fermentation
1,3 PDO[I]	**125 ktonne/y[3]**	**Petrochemical 1,3 PDO**	**+/-**	**Fermentation with genetically engineered organism[4]**
Isobutanol[J]	105 ktonne/yr[6]	Isobutanol based on propylene	-	Yeast fermentation by genetically engineered organism[6]
Itaconic acid[K]	41 ktonne/y[3]	Acrylic acid or maleic acid	--	Fermentation by means of fungi[5]
3-HPA[L]	40 tonne[6]	unknown	--	Dehydration – fermentation (fermentation pathway not known)[4]

[A] Ethylene has a global annual market volume of 127 Mtonne, of which currently a small fraction (0.2%) is biobased (Taylor et al., 2015). Ethylene is not a direct fermentation product, but can be produced via ethanol dehydration (Zhang & Yu, 2013).

[B] Ethanol is an important biofuel replacing gasoline. In 2015 world annual ethanol production increased ±4% to 98.3 billion litres, at the same time the production in Brazil reached a record of 30 billion litres (Seyboth et al. 2016). Around 18% of the ethanol production is for non-energy applications (Choi et al., 2015). For ethanol production various publication assess the economic performance of first, or second generation industrial processing, among others (Chovau, et al2013; Dias, al. 2011; Hamelinck, et al2005).

[C] Propylene is an important platform chemical, the production from biobased feedstock can occur via different processes (via ethylene, n-butanol, acetone, isopropanol, or via propane (Harmsen, et al2014)).

[D] With a current production capacity of 3 million tonne/year, the demand for new production capacity is limited as acetone is a co-product of the economic more attractive phenol (Straathof, 2014).

[E] For the production of adipic acid no detailed economic data was found.

[F] Isopropanol is mainly used as solvent with a total production around 2.3 Mtonne, and it is produced using propylene as feedstock (Straathof, 2014). Isopropanol via sugar fermentation is currently under development (Harmsen, et al2014).

[G] The estimated global market is projected to reach 599 ktonne in 2020 (Weastra, 2012). The market for succinic acid and its derivatives can even reach 6.2 Mtonne/year (theoretical upper limit) in case succinic acid will replace all other specific end use applications (Weastra, 2012). Important to note is that the study by Harmsen et al (2014) estimated the current succinic acid production at only 40kton/y, of which 1 kton/y was biobased in 2013.However, the study of Weastra estimated the potential increase in production capacity of biobased succinic acid to be 637 kton/y in 2020.

[H] Lactic acid is currently mainly used for the production of polylactic acid (PLA) (Straathof, 2014). The entire production of lactic acid is biobased (Taylor et al., 2015)

[I] Recently, 1,3 Propandiol (PDO) production by fermentation of glucose and glycerol has been developed (Straathof, 2014). Studies estimated that a large fraction is biobased (P. F. H. Harmsen et al., 2014; Taylor et al., 2015).

[J] The current market of isobutanol is approximately 21% biobased (Taylor et al., 2015).

[K] Itaconic acid is assumed to be 100% biobased production (Taylor et al., 2015), with a current market volume of 41 ktonne (P. F. H. Harmsen et al., 2014). With the wide diversity of substitution possibilities the total market volume is estimated as 6.2 Mtonne (Weastra, 2012).

[L] 3-Hydroxypropionic acid (HPA) is a C_3 platform chemical with derivatives for the commodity as well as the specialty chemicals market (Werpy, T. and Petersen et al., 2004). At the moment the production is limited to 40 tonne (Taylor et al., 2015).

References:

[1] (Straathof, 2014), [2] (Weastra, 2012), [3] (Harmsen, et al 2014), [4] (Werpy, and Petersen 2004) [5] (Paulien Harmsen & Hackmann, n.d.), [6] (Taylor et al., 2015)

Based on the criteria and the scoring in Table 6-1, ethanol (C_2H_6O), ethylene (C_2H_4), 1,3 propanediol ($C_3H_8O_2$) and succinic acid ($C_4H_6O_4$) are selected for an economic and GHG emission analysis. The four biobased products are assessed via use of first generation (sugarcane) and second generation (eucalyptus) processing. Only ethanol is also considered via the integrated first-and-second generation industrial processing. A simplified flowchart of the selected biobased platform chemicals and the main industrial processing steps is shown in Figure 6-1. In the supplementary information SI.1., more information is provided about the industrial processes used for the production of the selected biobased chemicals.

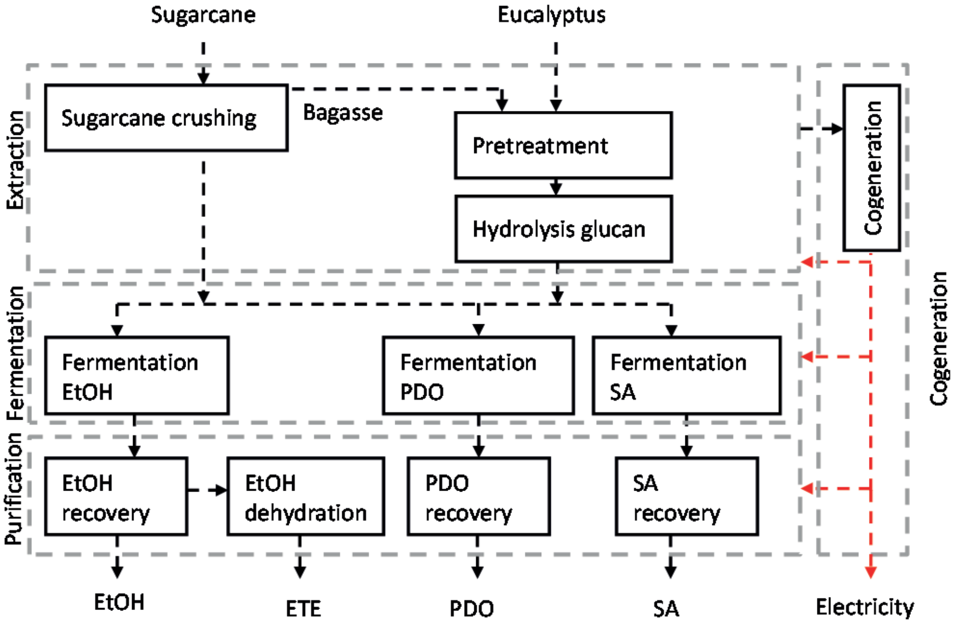

Figure 6-1, Simplified flowchart of the selected biobased platform chemicals and the main industrial processing steps, including the cogeneration unit for process steam and electricity.

6.3 Methods

This study aims to quantify and compare the production costs and GHG emission intensity of ethanol, ethylene, 1,3 propandiol, and succinic acid production using sugarcane and eucalyptus as biomass feedstock in Brazil, and compare them to their fossil reference. To enable a comparison among the different biobased production pathways and their fossil reference, a uniform approach and assumptions are applied. For this comparison, the production costs and GHG emission intensity are expressed in US$/kg final product and kg CO_{2eq}/kg final product respectively. In addition, the GHG emissions reduction (with respect to their fossil equivalent product) and potential total profit (compared to their fossil equivalent product) are expressed per hectare of feedstock production. These units enable a comparison between the different industrial processing pathways and between the utilization of sugarcane or eucalyptus as biomass feedstock.

The focus of this analysis is on the industrial processing of sugarcane and eucalyptus to biobased products, e.g. from feedstock delivery to factory gate. To calculate the costs and GHG emissions of each pathway, an inventory of all mass and energy inputs and outputs of each of the industrial pathway is made (see section 6.3.1). This also includes the quantification of the biobased product yield (BPY) per tonne biomass input; either tonne sugarcane (TC) or dry tonne eucalyptus. The production costs of the biobased products are the sum of the costs for capital depreciation, biomass feedstock, energy, labour, maintenance, and other operational costs (see section 6.3.2). The production costs of biobased products are compared to the prices of the fossil reference products. The GHG emissions of the biobased products include the GHG emissions of feedstock cultivation and transport, GHG emissions of other raw material consumption, operational GHG emissions, and GHG emissions related to energy demand or surplus. GHG emissions related to direct and indirect land use change are not included. The GHG emissions of the biobased products are compared to those from the fossil based equivalent products.

To enable a uniform comparison, the costs and GHG emission intensity of biomass feedstock supply, the scale of the industrial processing plant, the costs and GHG emission intensity of electricity use, and the main economic assumptions are equal for the different biobased processing pathways. Due to the large uncertainty of the costs and the GHG emissions of the (novel) biobased pathways and their fossil references, both a sensitivity analysis as well as an uncertainty analysis are performed. The results of these analysis quantify the potential range of production costs and GHG emissions of the biobased products given the uncertainty in the key parameters. The different ranges are compared to the range in factory gate production price and GHG emission intensity of the fossil reference products. The ranges of factory gate price and GHG emission intensity of the respective fossil references are based on a literature review.

Combining the production costs, fossil reference price, BPY, and the average biomass yield per hectare in Brazil results in the potential net profit per hectare in one year. Similarly, the net GHG emission reduction of each biobased processing pathway is calculated per hectare.

6.3.1 Mass and energy inventory

The mass and energy inventory includes the calculation of the biobased product yield (BPY), and the inventory of mass inputs and heat, steam, and electricity consumption or electricity surplus. The BPY per tonne of biomass feedstock is determined using the feedstock composition, maximum stoichiometric conversion and the industrial processing efficiencies, see Equation 1. First, the amount of available sugars in sugarcane and eucalyptus is quantified, based on published data regarding biomass composition. The stoichiometric mass efficiency is based on the simplified chemical equation of the conversion process, and represents the maximum conversion efficiency (theoretical upper limit) of sugars to the selected biobased chemical. A number of factors limit the amount of BPY that can be produced per tonne of biomass feedstock, namely: sugar extraction or biomass pretreatment, fermentation and the purification of the final product. The aggregated efficiencies of these main processing steps represent the mass conversion or processing efficiency of the individual steps and are based on available literature regarding conversion and product yield.

$$\mathrm{BPY} = \mathrm{S} \cdot \eta_{\mathrm{Ex}} \cdot \eta_{\mathrm{Fer}} \cdot \eta_{\mathrm{max}} \cdot \eta_{\mathrm{RP}}$$

Equation 1

Item	**Description**	**Unit**
BPY	Biobased Product Yield	Kg biobased product/tonne biomass feedstock
S	Sucrose or glucose content per tonne biomass feedstock	Kg sugar/tonne biomass feedstock
η_{Ex}	Sugar extraction efficiency	%
η_{Fer}	Fermentation efficiency	%
η_{max}	Maximum conversion efficiency	%
H_{RP}	Recovery and purification efficiency	%

Next to the BPY, an inventory of the major mass and energy inputs is made, which specifies the demand for yeast, chemicals, steam, fuel and electricity for the extraction, fermentation and recovery of the selected biobased chemicals. This inventory is based on the available literature regarding mass and energy inputs and normalized to tonne biomass feedstock input or kg final biobased product. Minor inputs, such as lubricants, are not quantified, but included in the operational costs via a fixed percentage of the fixed capital investment (FCI) as annual costs for minor industrial inputs.

6.3.2 Economic assessment

A discounted cash flow spreadsheet is employed to calculate the production costs of biobased products (BPC) of the different industrial processing pathways producing ethanol, ethylene, 1,3 propanediol and succinic acid. The cash flow include the expenses for sugarcane or eucalyptus feedstock, investment, maintenance, operational expenses, labour, and energy inputs, see Equation 2. The total capital investment (TCI) of an industrial processing pathway is the sum of the costs for the different processes required to produce the specific biobased product. For each processing step, as distinguished in Figure 6-1, the equipment costs (EC) are taken from literature, scaled with the scaling factors (see Equation 3), and multiplied with the appropriate Lang Factor (LF; ratio of TCI to the total purchased equipment costs). The annual expenses for minor operational inputs, maintenance, and labour are calculated as a fixed annual percentage of the TCI. The annual production of the biobased product of an industrial plant is the product of BPY, the scale of the industrial processing plant and annual operational hours (see SI.2). For energy expenses, it is assumed that the energy consumption not covered by the cogeneration unit is purchased externally. All costs are calculated in 2016 US dollar.

$$BPC = \frac{(\propto \cdot FCI) + OI + M + L}{BPY \cdot cap \cdot hours} + \frac{F}{BPY} - \left(\left(E_{production} - E_{consumption}\right) \cdot E_{price}\right)$$

Equation 2

Item	**Description**	**Unit**
BPC	Production costs of biobased product	US$/kg biobased product
ɑ	Capital recovery factor	%
FCI	Fixed Capital Investment	US$
OI	Annual operational inputs	US$/year
M	Annual maintenance costs	US$/year
L	Labour expenses per year	US$/year
CPR	Co-product revenues per year	US$/year
BPY	Biobased Product Yield	Kg biobased product/tonne sugarcane or Kg biobased product dry tonne eucalyptus
Cap	Industrial capacity	TC/hour or dry tonne/hour
Hours	Annual operational hours of the industrial plant	Hours/year
F	Feedstock costs	US$/tonne sugarcane or US$/dry tonne eucalyptus
$E_{production}$	Energy production in cogeneration unit	kWh/kg biobased product
$E_{consumption}$	Energy consumption of different processing steps	kWh/kg biobased product
E_{PRICE}	Energy price	US$/kWh

$$\mathrm{FCI} = \sum \left(\mathrm{Base\ EC} \cdot \left(\frac{\mathrm{Scale}}{\mathrm{Base\ scale}}\right)^{\mathrm{SF}}\right) \cdot \mathrm{LF}$$

Equation 3

Abbreviation	**Description**	**Unit**
FCI	Fixed Capital Investment	US$
LF	Lang Factor	[-]
EC	Equipment costs of the equipment installed	US$
Base EC	Equipment costs of the base scale	US$
Scale	Scale of equipment	Divers units; e.g. tonne/hour
Base scale	Base scale corresponding to the base EC	Divers units; e.g. tonne/hour
SF	Scaling factor of installed equipment (until it reaches maximum scale)	[-]

6.3.3 GHG emission intensity

GHG emission calculations methodologies for different types of bioenergy have been developed for decades (e.g. REFS). Some methods are included in legislation in e.g. the EU and the US (Hennecke et al., 2013; Soratana et al., 2014; Stichnothe, Schuchardt, & Rahutomo, 2014), and have very detailed and clearly defined rules on e.g. how to deal with allocation, and what is the fossil reference for comparison. For the life-cycle assessment of the production of biobased and fossil chemical, ISO standard 14044 has been developed(ISO, 2006). This is used as basis for the GHG emission quantification in this study.

This study focusses on biobased processing pathways with one main output: ethanol, ethylene, 1,3 PDO and succinic acid. Other outputs of the production pathways are considered as by-products. When considering one main product, the displacement method is usually selected for life-cycle analysis (J. Seabra et al., 2011). This means that for by-products of industrial processing pathways the potential displacement of GHG emissions are credited to the main output of the biobased production pathways. Electricity surplus results in avoided GHG emissions due to the substitution of Brazilian electricity from the -grid. Avoided GHG emissions are credited to the main biobased product output.

GHG emissions of biomass supply are included trough use of data published in other studies for sugarcane and eucalyptus cultivation and transport, combined with the biobased product yield. Industrial GHG emissions include the inputs for industrial processing and their respective GHG emission intensity. By summing the feedstock supply, industrial processing and energy GHG emissions and normalizing the results to the functional unit (i.e. 1 kg ethanol, ethylene, 1,3 PDO or succinic acid), the GHG emission intensity of biobased products are calculated, see Equation 4.

$$\text{GHG} = \frac{F_{GHG}}{BPY} + IP_{GHG} - \left(\left(E_{production} - E_{consumption}\right) \cdot E_{GHG}\right)$$

Equation 4

Abbreviation	**Description**	**Unit**
GHG	GHG emission intensity of biobased product	Kg $CO_{2\text{-}eq}$/kg biobased product
F_{GHG}	Feedstock GHG emission intensity	Kg $CO_{2\text{-}eq}$/tonne biomass
IP_{GHG}	Industrial processing GHG emissions	Kg $CO_{2\text{-}eq}$/kg biobased product
$E_{production}$	Energy production in cogeneration unit	kWh/kg biobased product
$E_{consumption}$	Energy consumption of different processing steps	kWh/kg biobased product
E_{GHG}	GHG emissions of energy consumption	Kg $CO_{2\text{-}eq}$/kWh
BPY	Biobased Product Yield	Kg biobased product/tonne biomass

6.3.4 Fossil reference

The production costs and GHG emission intensity of biobased ethanol, ethylene, 1,3 propanediol and succinic acid are compared to the costs and GHG emissions of the equivalent petrochemical reference products. As shown in Table 6-1 petrochemical gasoline, ethylene, 1,3 propanediol, succinic acid and maleic anhydride are selected as fossil reference products. Ethanol is considered as direct substitution to gasoline as 82% of the ethanol production is for energy applications (Choi et al., 2015). Therefore, ethanol is compared to gasoline based on the energy content. Biobased ethylene is expected to replace petrochemical ethylene. Similarly, the production of biobased 1,3 PDO and succinic acid is expected to replace their fossil based counterpart. However, as the fossil reference platform chemical for succinic acid depends on its derivate products, both petrochemical succinic acid and maleic anhydride are selected. The production costs and GHG emission intensity of the biobased products are compared to their equivalent fossil reference product on factory gate basis.

For factory gate petrochemical price ranges a relationship between crude oil prices and the price of petrochemical derivatives is considered in this study. To determine the price range of petrochemical reference products, first the price is determined based on available literature and databases. Second, this base value is then multiplied with the range in oil prices of the last 10 years and the price growth factors for basic chemicals or petroleum products. The price growth factors indicate the variation in price of a commodity with a doubling of the price of crude oil (Patel et al. 2013). The basis for using growth factors is that the price of petrochemical? commodities increases with increasing oil prices, as supported by the relationship of ethylene price in relation to crude oil price, as shown by (Haro et al., 2013).

The range in GHG emission intensity of petrochemical products is based on values found in literature. Important to note that the GHG emission intensity, expressed as CO_{2eq}, includes the factory gate GHG emissions and the combustion GHG emissions (anthropogenic GHG emissions) at the end-of-life use of the products. The combustion GHG emissions are based on the embedded fossil carbon in petrochemical products. The lowest and highest value for the GHG emission intensity of the fossil reference products found in literature are plotted in the results, this depicts the potential range of the GHG emission intensity of fossil reference products. This includes GHG emission intensity values for different geographical regions and different LCA allocation methods. The GHG emission reduction potential of a biobased production pathway is the difference between the GHG emission intensity of the fossil product and the biobased product.

6.3.5 Sensitivity and uncertainty analysis

In this study, data is taken from other publications to determine the BPY, production costs and GHG emission intensity of the biobased products. This data is prone to uncertainty, and varies according to their regional or temporal scope. The uncertainty of one or multiple parameters cannot directly be translated to the potential variation in production costs or GHG emission intensity. The impact of the variability and uncertainty of the different input parameters on the final result is addressed by both a sensitivity analysis and an uncertainty analysis

Firstly, the sensitivity of the most prominent parameters on the production costs and GHG emission intensity is determined by a single-parameter sensitivity analysis. The parameter variation is based on the range of the different key parameters found in literature. An early screening shows that the key parameters in this study are the feedstock costs and GHG emission intensity, biobased product yield, total investment, industrial scale and the price and GHG emission intensity of the energy consumed. The results of the sensitivity analysis show the impact of a single parameter variation on the production costs and GHG emission of a biobased product.

Secondly, a Monte-Carlo analysis is performed to quantify the confidence ranges of the production costs and GHG emission intensity of biobased products. For the production costs, the biomass feedstock costs, biobased product yield, energy price, industrial scale, and total capital investment costs are key parameters. For the GHG emission intensity, the GHG emissions of feedstock supply, energy GHG emissions and the BPY are considered key variables. Each variable has a specific probability distribution which is used in the Monte-Carlo analysis. The distribution for each parameter is discussed in section 6.4. This is based on the available data and likely distribution over the data range found. In the Monte-Carlo analysis, the key input parameters are varied according to their probability distribution at the same time. The result of the Monte-Carlo analysis are probability distributions for the production costs or GHG emission intensity of the biobased products. These results are plotted next to the ranges of the prices of their fossil reference product.

6.4 Data input

This section is structured along the data requirement for determining the BPY, energy use, economic data, GHG emission data, and fossil reference. Each subsection describes the data used in this analysis, the uncertainty associated with this data and the data sources. For the key parameters considered in the Monte-Carlo analysis the uncertainty or variation is describes as normal, triangular or uniform distributions[21].

6.4.1 Industrial conversion efficiency to biobased products

Table 6-2 includes the mass efficiencies fermentation, maximum stoichiometric mass yield, and the product recovery and purification efficiency to determine the BPY for ethanol, ethylene, 1,3 PDO and succinic acid. Based on the ranges for the different process efficiencies, and their probability distribution, the normal distribution for the BPY is determined (see Table 6-2).

Sugarcane ethanol is an established industry with multiple companies and a large amount of installed industrial processing facilities (Choi et al., 2015; J.G.G. Jonker et al., 2016). With decades of operational experience for sugarcane-to-ethanol industrial facilities, several studies have discussed the historic development of industrial efficiency (van den Wall Bake et al., 2009; Walter, 2008), survey operational industrial plants annually (Eduardo & Xavier, 2012; XAVIER et al., 2010; XAVIER, SONODA, ZILIO, & MARQUES, 2011), and studied current economic and GHG emission performance (Cavalett et al., 2011; Dias, Cunha, et al., 2011; J. Seabra et al., 2011; Ioannis Tsiropoulos et al., 2014). Therefore, the BPY, (de Souza Dias et al., 2015; Walter, 2008) and steam and electricity consumption (Dias, Cunha, et al., 2011) can be calculated with low level of uncertainty.

The eucalyptus to ethanol production process is proposed in different studies (Gonzalez, , et al. 2011; Gonzalez, , et al. 2011; Hamelinck, et al 2005; J.G.G. Jonker, F 2014). However, to our knowledge, no industrial plants are constructed using eucalyptus as feedstock. Although the scientific body is extensive, the range found for ethanol yield on ligno-cellulosic feedstock is considerable, with medium uncertainty regarding the BPY (Chovau et al., 2013).

The production pathway of ethylene via ethanol (ethanol dehydration to ethylene) is currently being commercialized by several companies (Choi et al., 2015). No information was found about the operational yields, costs or GHG emissions of these industrial plants. Desktop studies for ethanol dehydration to ethylene all show high BPY (all over 97% of stoichiometric efficiency) (Cameron, Le, Levine, & Nagulapalli, 2012; Morschbacker, 2009; Zhang & Yu, 2013). Therefore, the ethanol to ethylene production process is qualified as low uncertainty level, but the uncertainty level of the entire production pathways depends on the uncertainty qualification given to the ethanol production as well.

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[21] Different probability distributions; normal; a common probability distribution, uniform; where all intervals have the same probability, triangular; a triangular shaped probability distribution, where the triangular is shaped by the upper-, and lower limit, and a mode.

The detailed published data found for the production of succinic acid from sucrose is limited to Efe et al (2013). The efficiencies of the industrial processing steps are based on Efe et al (2013). No techno-economic data was found in literature for the production of 1,3 PDO using sugarcane or eucalyptus as feedstock. The conversion rate of sugar to 1,3 PDO resulted from lab experiments are used to calculate the BPY of 1,3 PDO production. Therefore, the uncertainty is considered high for the BPY of 1,3 PDO and succinic acid production.

Table 6-2. Extraction, fermentation and product recovery efficiencies and resulting BPY for the different industrial processing pathways.

Parameter	Unit	Base value	Range	Probability Distribution	Reference
Sucrose content SC	Kg/TC	145^{A}	130-165^{B}	Uniform	(Dias, Cunha, et al., 2011)
Glucan content EU	Kg/dry tonne	495	495	-	(Hamelinck et al., 2005)
Sucrose extraction	%	96	95-97^{C}	Uniform	(Walter, 2008)
Fermentation to ethanol	%	92	88-94.5^{D}	Uniform	(J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014)
Stoichiometric ethanol	%	51^{E}	-	-	(Carioca & Leal, 2011)
Distillation	%	99	97-99.5^{F}	Uniform	(Walter, 2008)
BPY 1G Ethanol	**Kg/TC**	**64**	**49.5-75.7 (100%)** **56.0-73.0 (90%)**	**Normal (mean 63.4, Std Dev 4.65)**	
Pretreatment of eucalyptus	%	95	90-100^{G}	Uniform	(Humbird et al., 2011)
Hydrolysis of eucalyptus	%	80	75-90^{H}	Uniform	(Humbird et al., 2011)
BPY 1+2G Ethanol	**Kg/TC**	**91**	**71.6-101.5 (100%)** **78.1-94.6 (90%)**	**Normal (mean 86.2, Std Dev 5.07)**	
BPY 2G Ethanol	**Kg/dry tonne**	**243**	**192.4-281.1 (100%)** **203.8-267.1 (90%)**	**Normal (mean 234.8 Std Dev 19.74)**	
Stoichiometric ethylene	%	61	-	-	(P Harmsen et al., 2014)
Ethanol dehydration	%	98	96-100%^{I}	Uniform	(Haro et al., 2013)
BPY 1G ETE	**Kg/TC**	**37**	**31.1-37.9 (100%)** **33.5-42.5 (90%)**	**Normal (mean 38.5, Std Dev 2.84)**	

PBY 2G ETE	**Kg/dry tonne**	**140**	**114.2-170.0 (100%)** **121.6-160.0 (90%)**	**Normal (mean 140.3, Std Dev 12.0)**	
Stoichiometric 1,3 PDO	%	84	-	-	
Fermentation 1,3 PDO	%	61	55-67[J]	Uniform	
Recovery 1,3 PDO	%	90	80-100[K]	Uniform	(J. Posada et al., 2013)
BPY 1G 1,3 PDO	**Kg/TC**	**62**	**45.4-88.1 (100%)** **53.0-76.7 (90%)**	**Normal (mean 65.0, Std Dev 7.2)**	
BPY 2G 1,3 PDO	**Kg/dry tonne**	**207**	**140.0-272.4 (100%)** **162.0-241.5 (90%)**	**Normal (mean 198.6, Std Dev 24.1)**	
Stoichiometric succinic acid	%	112	-	-	
Fermentation succinic acid	%	75	62-110[L]	Uniform	
Recovery succinic acid	%	92	70-95[M]	Uniform	
BPY 1G succinic acid	**Kg/TC**	**107**	**54.0 159.2 (100%)** **70.1-133.3 (90%)**	**Normal (mean 99.5, Std Dev 19.4)**	
BPY 2G succinic acid	**Kg/dry tonne**	**326**	**169.1-497.5 (100%)** **216.1-416.5 (90%)**	**Normal (mean 303.0, Std Dev 61.0)**	

[A] Base value sugar content of sugarcane similar to (Dias,et al. (2011).

[B] Sugar content varies within a harvest season, between genotypes, and between years (Leal et al., 2012; MINISTÉRIO da et al., 2010).

[C] In recent decades the extraction yield increased from 92 to 96%, being 97.5% as the upper limit (Walter, 2008).

[D] According to Walter (2008) the fermentation yields increased from 88% to 91%, with 93% being the upper best practise. Due to the production of by-products, 94.5% is considered the upper practical limit (Carioca & Leal, 2011).

[E] The maximum stoichiometric mass conversion efficiency of sugar to ethanol is 51% (Carioca & Leal, 2011).

[F] Due to higher ethanol content in fermentation broth and technology improvement the distillation of ethanol reached 99% efficiency today (Walter, 2008).

[G] During pretreatment small amounts of sugars are converted to other products (Humbird et al., 2011)

[H] Hydrolysis includes the reaction of glucan to glucose (ratio 1 – 1,11). A small fraction of the glucan is converted to glucose oligomer and cellobiose (Humbird et al., 2011).

[I] The dehydration of ethylene is reported to have a high mass conversion efficiency (Haro et al., 2013; Nitzsche et al., 2016). Due to the lack of data about the maximum practical limit, the upper limit is set to 100%.

[J] Three studies (Anex & Ogletree, 2006; DuPont Tate & Lyle, n.d.; Urban & Bakshi, 2009) use 0.51 kg/kg. No information was found on the range. A variation of 10% was assumed due to the agreement between earlier mentioned studies. See also potential increase in fermentation yield as used in the study of Stegmann (2014).

[K] Data is lacking; a range of 80 to 100% is assumed to assess the potential impact of the variation in the efficiency of recovering on the final results. Include various steps; different filtration steps, ion-exchange, evaporation, distillation and hydrogenation (Molel, Phillips, & Smith, 2015; J. Posada et al., 2013)

[L] See the review by Cheng, et al(2012) which reported yield (g/g) of succinate on glucose.

[M] Cheng, , et al. (2012) showed different extraction rates, commonly vary between 70 and 95. The latter one being a chain of extraction processes.

6.4.2 Energy consumption of various configuration

Table 6-3 lists the energy demand or energy surplus of the different industrial processing facilities. For data regarding electricity production, use and surplus, several studies are published (i.a. Dias, Cunha, et al. 2011; Dias, da Cunha, et al. 2011; Ensinas et al. 2007). These studies showed little variation in surplus electricity. For ethylene production the studies of Haro et al (2013) and; Nitzsche, et al (2016) are considered, again with low level of variation in the energy demand. The energy consumption for the production of 1,3 PDO is based on Dunn et al, 2015). For succinic acid, a detailed assessment is provided by Alves et al. (2016), which is in line with Efe et al (2013). The variability and uncertainty of the costs and GHG emissions of energy consumption was considered by the variation in price and GHG emission intensity of electricity, see section 6.4.4.

Table 6-3 Energy demand and surplus energy for the processing of sugarcane into ethanol, ethylene, 1,3 Propanediol and succinic acid.

Process	**Value**	**Unit**	**Reference**
Steam production sugarcane bagasse	616 [A]	kg steam/TC	Own calculation
Steam production eucalyptus	2579	Kg steam/dry tonne	Own calculation
Steam to electricity conversion	3 [Z]	kg steam/kWh	(Quora, 2016)
Steam use cane reception	171 [B]	kg steam/TC	(Ensinas et al., 2007)
Electricity own use cane reception	16 [C]	kWh/TC	(Dias, Cunha, et al., 2011)
Steam use ethanol distillery	107 [B]	kg steam/TC	(Ensinas et al., 2007)
Electricity use ethanol distillery	30 [C]	kWh/TC	(Dias, Cunha, et al., 2011)
Electricity ethanol dehydration	0.21 [D]	kWh/L ethanol	(Haro et al., 2013; Nitzsche et al., 2016)
Fuel ethanol dehydration	1.34 [E]	MJ/L ethanol	(Arvidsson, 2016; Haro et al., 2013)
Steam demand for ethanol dehydration	3.96	MJ/kg ethylene	(Arvidsson, 2016)
Electricity consumption for 1,3 Propanediol fermentation and purification	0.0323[J]	kWh/kg PDO	(Jennifer B. Dunn, Felix Adom, Norm Sather, Jeongwoo Han, 2015)
Natural gas use for 1.3 Propanediol fermentation and purification	15.13[K]	MJ/kg PDO	(Jennifer B. Dunn, Felix Adom, Norm Sather, Jeongwoo Han, 2015)
Succinic acid natural gas use	3.46	MJ/kg succinic acid	(Alves et al., 2016)
Succinic acid steam use	20.15	Kg MP	(Alves et al., 2016)

		steam/kg succinic acid	
Succinic acid electricity use	0.538 [I]	kWh/kg succinic acid	(Alves et al., 2016)

[A] Using a fibre content of 14% (140 kg dry bagasse/TC), moisture content of 50%, LHV of 7.565 (Dias, Cunha, et al., 2011) and boiler efficiency of 80% (steam delta H of 2.8 MJ/kg).

[B] Steam demand for an improved industrial processing plant, reducing the steam demand from 540 to 278 kg steam/TC (Ensinas et al., 2007). According to (Ensinas et al., 2007) steam demand is 23.7 kg/s for juice treatment, and 0.1 and 14.8 kg/s for sugar drying and distillation respectively (500 TC/hour capacity plant).

[C] Electricity demand based on the electricity use for cane reception as specified by Dias, Cunha, et al. 2011).

[D] Electricity demand ethanol dehydration is 4 MW for a dehydration unit with a capacity of 150 M/year (13 MW for 500 ML/year) (Haro et al., 2013). The range of electricity demand ranges from 0.18 – 0.33 kWh/kg ethylene (Arvidsson, 2011; Haro et al., 2013).

[E] Natural gas demand (used together with fuel gas in a boiler) is 7 MW for a dehydration unit with a capacity of 150 ML/year (24 MW for 500 ML/year) (Haro et al., 2013).

[J] Electricity use for the conversion of glycerol to 1.3 PDO is 0.1 MMBtu/ton (Jennifer B. Dunn, Felix Adom, Norm Sather, Jeongwoo Han, 2015).

[K] Natural gas input for the process described by (Jennifer B. Dunn, Felix Adom, Norm Sather, Jeongwoo Han, 2015), is set to 13 MMBtu/ton.

[Z] Steam consumption for the production of electricity (Quora, 2016)

6.4.3 Economic data

Equipment and total investment costs for the different processing components

Table 6-4 presents an overview of the equipment costs of the individual processing steps of the different industrial processing pathways to produce ethanol, ethylene, 1,3 propanediol or succinic acid. This overview includes the equipment costs, and the Lang Factors applied for each processing step. For the base value, the industrial scale is set to 500 TC/hour for sugarcane, in line with (Dias, Cunha, et al., 2011), with a scale range set to 100 – 1000 TC/hour. Considering the HHV of sugarcane stalks, as described in (Leal et al., 2012), this scale range corresponds to 138 - 1383 MW. For eucalyptus, the same scale (MW input) is used, this translates into a range of 7.7 – 77 dry tonne/hour for eucalyptus processing.

Economic data is inherently uncertain. The data for first generation industrial production taken from (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014) is in line with (Dias, Cunha, et al., 2011; Júnior et al., 2009; Macrelli et al., 2012). The equipment costs for second generation industrial ethanol production are medium uncertain, as also indicated by (Chovau et al., 2013). The most important variation results from the selection of technology which also influences the BPY and investment costs.

Results of economic assessments of ethanol dehydration (Haro et al., 2013; Nitzsche et al., 2016) are in the same range. However, uncertainty increases at larger scales and the maximum scale to which the scaling factors can be applied is uncertain. For the capital investment of ethanol and ethylene production an uncertainty range of +/- 25% is applied, similar to (Mariano et al., 2013).

Table 6-4, Equipment costs, base scale, maximum scale and scaling factors for the different industrial processing pathways.

Unit	Equipment	TCI (MUS$)	Lang factor	Base capacity	Max scale	Scaling factor
Sugarcane crushing[A]	23 MUS$	55	3	500 TC/hour	500 TC/hour	0.64
Fermentation + ethanol recovery[A]	27 MUS$	74	3	44,5 m^3/hour	25 m^3/hour	0.83
Cogeneration[A]	37 MUS$	99	3	140 dry tonne/hour	-	0.75
Ethanol – ethylene dehydration[B]	7.3 MUS$	29	4	8764 kg ethanol/hour	-	0.65
Handling and pretreatment ligno-cellulosic biomass[C]	22 MUS$	88	4	50 dry tonne/hour	80 dry tonne/hour	0.7
Hydrolysis[C]	4.3 MUS$	17.2	4	50 dry tonne/hour	80 dry tonne/hour	0.6
Fermentation and 1,3 PDO recovery[D]	5.35 MUS$	22.28	4	688 kg PDO/hour	-	0.7
Fermentation and succinic acid recovery[E]	47.11 MUS$	183	4	5313 kg SA/hour	5500 kg SA/hour	0.7

[A] For sugarcane crushing, the study of (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014) described in detail the equipment costs, capacity, and scale.

[B] (Haro et al., 2013; Nitzsche et al., 2016)

[C] (Nitzsche et al., 2016)

[D] (Gargalo, Carvalho, et al., 2016)

[E] based on (Alves et al., 2016; Efe et al., 2013)

The detailed published data found for the total investment costs of succinic acid production is limited to (Efe et al., 2013; Gargalo, Carvalho, et al., 2016). These studies agree on the BPY, but for energy consumption, capital investment cost and operational costs a wide range is found in these studies. In this study it is assumed that the economic and GHG emission data for succinic acid production from sucrose have a high uncertainty. Only one study was found using eucalyptus (Alves et al., 2016). However, it is assumed that the data on succinic acid production from eucalyptus is highly uncertain. Economic data and energy consumption for 1,3 PDO production is based on studies using glycerol as feedstock (Gargalo, Carvalho, et al., 2016; Gargalo, Cheali, Posada, Gernaey, & Sin, 2016), or studies addressing 1,4 butanediol (BDO) production (Koutinas et al., 2016). The uncertainty of equipment costs and the FCI are expressed as normal distribution. The base value is considered as mean value of the normal distribution, with a standard deviation corresponding to 5% of the FCI for ethanol and ethylene and a standard deviation corresponding to 10% of FCI for 1,3 PDO and succinic acid. Such standard deviation corresponds roughly to +/- 15% and 30% variation

Biomass feedstock supply costs and GHG emission intensity and operational costs and GHG emissions of industrial processing.

Table 6-5 shows the supply costs and GHG emission intensity of sugarcane and eucalyptus feedstock. Furthermore, the operational costs and known GHG emission intensity of industrial processing is depicted. For 1,3 propanediol and succinic acid the industrial operational costs are not known. It is assumed that the annual costs of minor operational inputs are covered by the fixed percentage of operational expenses, as discussed in section 6.3.1.

Table 6-5, Feedstock supply and industrial operation costs and GHG emissions

Item	**Unit**	**Value**	**Range**	**Reference**
Sugarcane cultivation	US$/TC	31^{A}	Normal distribution, st. dev. 0.45	(Eduardo & Xavier, 2012; Mariano et al., 2013)
	kg CO_2/TC	26^{C}	Uniform; min 29.6, max 35.5	
Sugarcane transport	US$/TC	6^{E}	-	(J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014; J.G.G. Jonker et al., 2016)
	Kg CO_2/TC	2.45^{G}	-	(J.G.G. Jonker et al., 2016)
Eucalyptus supply	US$/tonne	48^{I}	Normal distribution, st. dev. 0.91	(J.G.G. Jonker et al., 2016)
	Kg CO_2/tonne	22.45^{K}	Uniform; min 19.1, max 25.8	(J.G.G. Jonker et al., 2016)
Electricity	US$/MWh	61	Uniform; min 42, max 80	(Mariano et al., 2013)

	Kg CO_2/kWh	0.22	Uniform, min 0.22, max 0.65	(I. Tsiropoulos et al., 2015)

[A] The average sugarcane price between 2001 – 2011 is 26 US$$_{2011}$/tonne (Cavalett et al., 2011). For today we consider a value of 30 US$/tonne, based on (J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014; Mariano et al., 2013).
[C] Sugarcane cultivation, excluding trash burning and cane transportation, values for 2005-2006 season (Macedo et al., 2008).
[E] Considering an average distance between field and industrial plant of 30 km and truck transport parameters as specified in (J.G.G. Jonker et al., 2016).
[G] Sugarcane transport, using distance (23km), truck fuel efficiency (0.019 L/t km), and diesel GHG emission intensity of 3.87 kg CO_2/L (J.G.G. Jonker et al., 2016; Macedo et al., 2008).
[I] Although there is currently no market for sugarcane trash, in this analysis a potential price is included, based on the studies mentioned, mainly referring to industry experts.
[K] Assuming the same GHG emission intensity for trash transport (wet) as wet sugarcane stalks, see above.

6.4.4 Fossil reference

Fossil reference price

The prices of fossil reference fuels and chemicals are used to compare the selected biofuel and biobased chemicals, see Table 6-6. The cost ranges of fossil reference products are determined using the crude oil price variation as basis, as discussed in section 6.3.4.

Table 6-6. Price of fossil reference products and Brazilian electricity

Item	Base value	Range[A]	Unit
Gasoline fuel fossil reference	0.55[B]	0.44 – 1.42	US$/kg
Ethylene fossil reference	1.2[C]	0.78 – 1.62	US$/kg
1.3 Propanediol	2.02[D]	1.24 – 2.80	US$/kg
Succinic acid	2.5[E]	1.54 – 3.46	US$/kg

[A] Using the crude oil price variation of the last 10 years as proxy for the price variation, using the price increase factor of 0.77, and 0.96 for electricity and petroleum products respectively.
[B] Assuming the costs of crude oil and refining are similar in different parts of the world. Using the approach of (van Vliet, Faaij, & Turkenburg, 2009) to calculate the production costs of gasoline based on the crude oil price: a price markup of 30% for refining is used. An oil price range of 40 to 130 US$/bbl (Haro et al 2013) is used, with 50 US$/bbl as current price (IndexMundi, 2017). The costs for taxes and distribution are not included. The costs shown here are per kg fossil product, however, to compensate for the difference in energy content to fuel characteristics are used; ethanol (density 0.79 kg/L, 30 MJ/kg), gasoline (0.75 kg/L, 46 MJ/kg) (Faaij, 2006)
[C] The price variation of the ethylene market price varied between 2006 and 2012 range 719-1850 US$/tonne (oil price variation between 40-130 US$/bbl) (Haro et

al., 2013).
[D] Average price for 1.3 PDO in US$/kg, in the study of (Gargalo, Carvalho, et al., 2016) with a standard deviation of 0.35 is considered.
[E] According to (Weastra, 2012) the price of petrol based succinic acid varies between $ 2.4 – 2.6/kg depending on the purity and quality of the succinic acid. (Pinazo, Domine, Parvulescu, & Petru, 2015) reported the production costs of maleic anhydride based succinic acid as 2.554 €/kg succinic acid. Biobased succinic acid is slightly more expensive ($ 2860 – 3000/metric tonne) (Weastra, 2012). Average price for succinic acid in US$/kg, with a standard deviation of 0.23 (Gargalo, Carvalho, et al., 2016).

Fossil reference GHG emission intensity
The total factory gate GHG emissions of the petrochemical products are expressed as CO_{2eq} emissions per kg product, see Table 6-7.

For *gasoline*, the processing GHG emissions are 12.5 gram CO_{2eq}/MJ_{fuel}, while the combustion emissions are 69.3 gram CO_{2eq}/MJ_{fuel} (Macedo et al., 2008). Total GHG emissions of gasoline are 81.77 gram CO_{2eq}/MJ_{fuel} which are in line with the values 69.9 and 96.9 gram CO_{2eq}/MJ_{fuel} reported by (Cavalett, Chagas, Seabra, & Bonomi, 2013; Hill et al., 2006; J. Seabra et al., 2011). To compensate for lower energy content of ethanol compared to gasoline, a correction factor between 1.3 and 1.6 litre ethanol/litre conventional gasoline is applied, depending on the car engine and percentage ethanol in the gasoline-ethanol fuel mix. The higher heating value of gasoline is based on the study of (Faaij (2006).

Reported values for GHG emissions of ethylene production are between 710 – 1800 gram CO_{2eq}/kg ethylene (Ghanta, Fahey, & Subramaniam, 2013; Liptow & Tillman, 2009; Jon McKechnie, Pourbafrani, Saville, & MacLean, 2015; M. Patel et al., 2006; PlasticsEurope, 2012). For ethylene production, the GHG emissions are dominated by the energy (fuel and electricity) consumption, mainly in the steam cracker (Ghanta et al., 2013; Liptow & Tillman, 2009). The embedded carbon in ethylene is equal to 3.09 kg CO_{2eq}/kg ethylene (based on C-content of 84.3%), in line with data reported by (Jon McKechnie et al., 2015).

For the production of fossil *1,3 PDO,* different production pathways exist, hydroformylation of ethylene oxide is the dominant pathway (EC European Commission, 2015). For this analysis, the carbon embedded in PDO (based on chemical structure) is considered being equivalent to 1.736 kg CO_{2eq}/kg PDO. A literature review found four studies reporting on the GHG emission intensity of factory gate fossil PDO (Anex & Ogletree, 2006; M. Patel et al., 2006; Stegmann, 2014; Urban & Bakshi, 2009). By adding the embedded CO_2 to the results presented in the study of (M. Patel et al., 2006), the total GHG emission intensity of all studies is in the range of 4.04 – 9.4 kg CO_{2eq}/kg PDO (Anex & Ogletree, 2006; M. Patel et al., 2006; Stegmann, 2014; Urban & Bakshi, 2009). The upper level of this range is found in (Urban & Bakshi, 2009), using a process LCA for a production facility in Lousiana, USA. Using the same geographic location but a hybrid LCA approach, the GHG emission intensity of fossil PDO would decrease to 6.7 kg CO_{2eq}/kg PDO (Urban & Bakshi, 2009). As it not clear if this upper level includes the embedded carbon, which is potentially emitted to the atmosphere as CO_2, this level can even increase to 11.14, which in line with data presented by (Jennifer B. Dunn, Felix Adom, Norm Sather, Jeongwoo Han, 2015).

The amount of studies presenting the GHG emission intensity of succinic acid is limited. Succinic acid is mainly produced by hydrogenation of maleic acid, which is produced by the oxidation of benzene or butane (Ullmann, 2005). Only two studies were found on the GHG emission intensity, of which one presented the cradle-to-grave GHG emissions. By including the embedded CO_{2eq} in succinic acid, the GHG emission range found is between 3.43 – 8.59 kg CO_{2eq}/kg succinic acid (Cok et al., 2013; M. Patel et al., 2006). Considering the potential derivatives for succinic acid, also maleic anhydride can be considered as fossil reference, which has a GHG emission intensity of 3.58 – 6.80 kg CO_{2eq}/kg succinic acid (Cok et al., 2013; M. Patel et al., 2006). For both products, the large non-renewable energy consumption (32.7 and 60.8 MJ/kg succinic acid and maleic anhydride respectively) dominates the GHG emissions (Cok et al., 2013).

Table 6-7, GHG emissions of fossil reference chemicals

Item	**Total GHG emissions**	**Unit**	**Reference**
Gasoline	1.52 – 2.59	kg CO_{2eq}/L ethanol equivalent	(Cavalett et al., 2013; Hill et al., 2006; J. Seabra et al., 2011)
Ethylene	3.8 – 4.89	kg CO_{2eq}/kg	(Ghanta et al., 2013; Liptow & Tillman, 2009; Jon McKechnie et al., 2015; M. Patel et al., 2006; PlasticsEurope, 2012)
1,3 PDO	4.04 – 9.4	kg CO_{2eq}/kg	(Anex & Ogletree, 2006; M. Patel et al., 2006; Urban & Bakshi, 2009)
Succinic acid	3.43 – 8.59	kg CO_{2eq}/kg	(Cok et al., 2013; M. Patel et al., 2006)

6.5 Results

6.5.1 Techno-economic results industrial processing pathways

Table 6-8 shows the fixed capital investment (FCI), biobased product yield (BPY), and electricity surplus for the selected sugarcane and eucalyptus processing pathways. The steam production in the cogeneration unit is based on the amount of sugarcane bagasse or eucalyptus residues and results in 0.62 tonne steam/TC or 2.6 tonne steam/dry tonne eucalyptus. When sugarcane bagasse is utilized for ethanol production the steam production is reduced to 396 kg steam/TC. The steam production can be used for process steam demand, or converted to electricity. The electricity can also be used for process electricity demand, the surplus electricity is sold to the grid. Both the PBY as the BPC are shown for a 90% confidence interval. Given the high glucan content, the BPYs of the eucalyptus production pathways are higher compared to the sugarcane pathways. Due to the larger uncertainty of the conversion efficiencies, the BPY range for 1,3 PDO and succinic acid production is larger compared to ethanol and ethylene production. The higher FCIs for the production pathways of 1,3 PDO and succinic acid are predominantly caused by the high equipment costs of the product recovery and purification.

Table 6-8, Range of biobased product yield, biobased production costs, fixed capital investment base value and electricity surplus for the different industrial processing pathways.

Feedstock	**Biobased product**	**BPY range 90% Kg biobased product/tonne biomass**	**Fixed capital investment base value (MUS$)**	**Electricity surplus (kWh/tonne biomass)**	**BPC 90% US$/kg biobased product**
Sugarcane	Ethanol 1G	57 – 72	245	67	0.60 – 0.83
Sugarcane	Ethanol 1+2G	79 – 96	322	-44	0.60 – 0.77
Eucalyptus	Ethanol 2G	204 – 268	174	100	0.83 – 1.23
Sugarcane	Ethylene	34 – 43	300	41	1.10 – 1.57
Eucalyptus	Ethylene	122 – 161	203	-5	1.64 – 2.23
Sugarcane	1,3 PDO	54 – 78	692	-242	1.25 – 1.74
Eucalyptus	1,3 PDO	16 – 241	271	-1211	1.72 – 2.73
Sugarcane	Succinic acid	71 – 135	1995	-585	1.68 – 3.40
Eucalyptus	Succinic acid	215 – 415	565	-2250	1.56 – 3.15

6.5.2 Biobased production costs breakdown

The contribution of the different cost components to the production costs of the different industrial pathways for the production of ethanol, ethylene, 1,3 PDO and succinic acid is shown in Figure 6-2. The main cost elements of the total biobased production costs are biomass feedstock, capital investment, energy (as co-product or as net energy consumption), and the processing inputs. Feedstock costs decrease with increasing biobased product yield (BPY). For example, the high glucan content and high conversion efficiency result in a low share of feedstock costs for succinic acid production using eucalyptus. Compared to ethanol production, the other industrial pathways result in a higher share of capital depreciation. For eucalyptus processing, the costs associated with enzymes for pretreatment and hydrolysis result in a large contribution of processing inputs to the total production costs. The fermentation and recovery of 1,3 PDO and succinic acid require a significant amount of steam and electricity. This energy demand is partly covered by the use of bagasse from sugarcane or the residues from eucalyptus (mainly lignin), but is not sufficient to meet the energy demand.

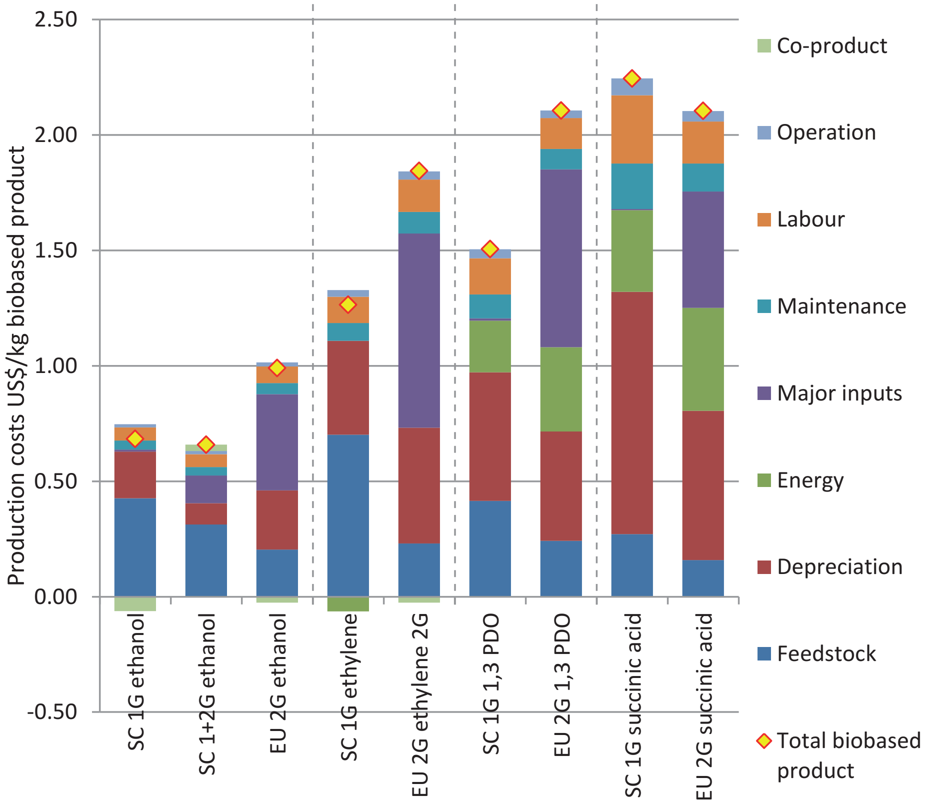

Figure 6-2 Contribution to the production costs of ethanol, ethylene, 1,3 PDO and succinic acid production using sugarcane and eucalyptus feedstock.

6.5.3 Sensitivity analysis for key economic parameters

A sensitivity analysis is performed on the variables BPY, feedstock costs, total investment costs, scaling, and the energy price, to analyse their influence on the total production costs and GHG emission intensity. The result are plotted in various spider diagrams, see Supplementary Information SI.3. The variation in BPY has the largest impact on the production costs as this varies the annual product output and in that way impacts the production costs. However, only the production of 1,3 PDO and succinic acid have a potentially large range in BPY. After the BPY, the production costs for first generation ethanol, first-and-second generation ethanol, and sugarcane ethylene are most impacted by the sugarcane feedstock costs. For the other industrial processing pathways their industrial production costs are most impacted by the variation in the FCI and electricity price.

6.5.4 Range of biobased production costs

The production cost ranges of the biobased products and of the prices of the petrochemical equivalent products are shown in Figure 6-3. Within the ranges of the biobased product costs, the mean production costs and the production cost ranges for 90%, 80% and 60% confidence interval are distinguished. The different levels of probability show the robustness of the results according to the considered data ranges. Due to larger uncertainty in BPY, total investment costs and energy price, the more complex biobased products result in a wider range for the production costs.

The production cost of ethanol is in the range of 0.64 – 1.10 US$/kg ethanol (60% confidence) for first generation, integrated first-and-second generation, and second generation industrial processing of sugarcane and eucalyptus. This cost range is generally higher than the factory gate prices of gasoline; 0.29 – 0.92 US$/kg ethanol equivalent. The costs of biobased ethanol is in the same range as gasoline at high crude oil prices (130 US$/bbl) and when biomass feedstock costs should be low in combination with low total capital investment costs. Especially for first generation ethanol production, sugarcane feedstock costs are approximately two-thirds of the total ethanol production costs. The ethylene production costs found in this study are in the range of 1.18 – 2.05 US$/kg ethylene. In comparison, the fossil ethylene production price range is 0.72 – 1.85 US$/kg ethylene. As the BPY of ethylene is lower compared to ethanol and the additional dehydration unit requires both more capital investment and larger amount of process energy, the ethylene production costs are almost twice as high compared to ethanol production costs. For 1,3 PDO, the biobased production costs are in the range of 1.37 – 2.40 US$/kg PDO, which is well within the range of the calculated petrochemical PDO price. Also, the base value of production costs of biobased PDO using sugarcane is lower than the base value of petrochemical PDO. Similar to PDO, the biobased production costs of succinic acid using sugarcane and eucalyptus are between 1.91 – 2.57 US$/kg succinic acid. This is within the range of the petrochemical succinic acid prices found. More importantly, the base value costs are lower compared to the base value costs of petrochemical succinic acid. Due to the higher uncertainty in BPY, FCI and energy consumption (and their impact on total production costs) the ranges of the 60, 80 and 90% confidence are larger for 1,3 PDO and succinic acid compared to the range of ethanol and ethylene.

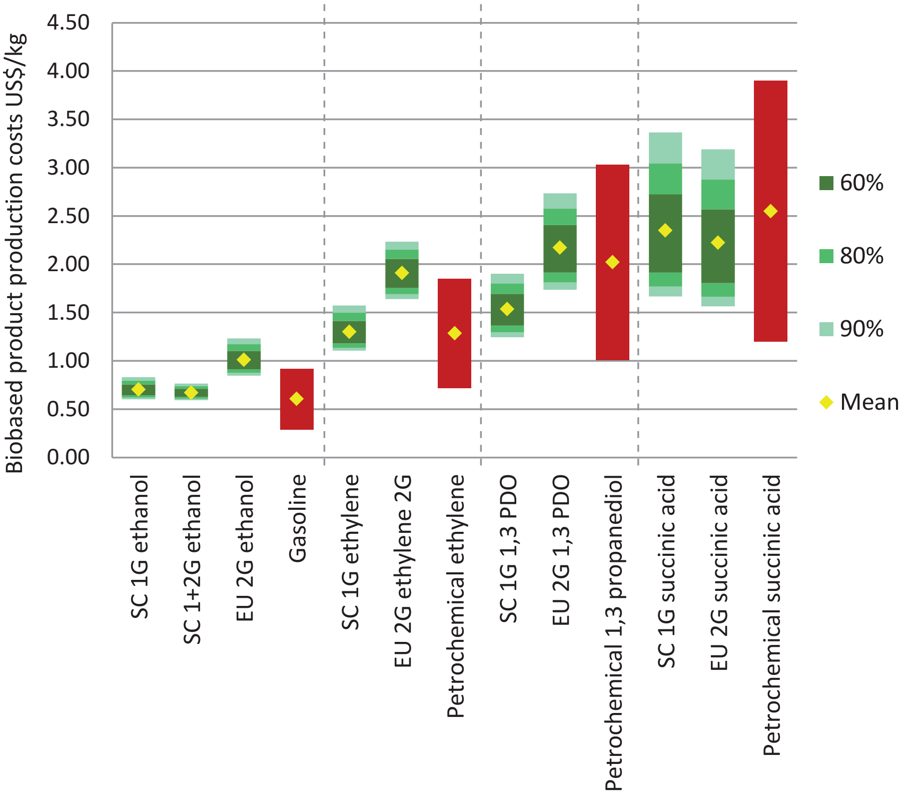

Figure 6-3 Uncertainty ranges) of production costs of the different biobased product and their respective fossil references

6.5.5 GHG emission breakdown

The mass and energy inventory was used to determine the biobased product yield and the GHG emissions, expressed in kg $CO_{2\ \text{EQUIVALENT}}$ per kg biobased product at the factory gate. GHG emissions include the emissions related to feedstock supply, industrial processing and the emissions associated with the additional steam, heat and electricity demand. For the processing of sugarcane to ethanol, eucalyptus to ethanol and sugarcane to ethylene, the electricity surplus results in negative emissions due to the electricity surplus. Similar to the economic performance, the contribution from the cultivation stage (i.e. GHG emissions per kg final product) are reduced with higher biobased product yield. For the production of 1,3 PDO and succinic acid, the steam and electricity demand (not covered by the cogeneration unit) result in a large amount of GHG emissions associated with steam and electricity consumption.

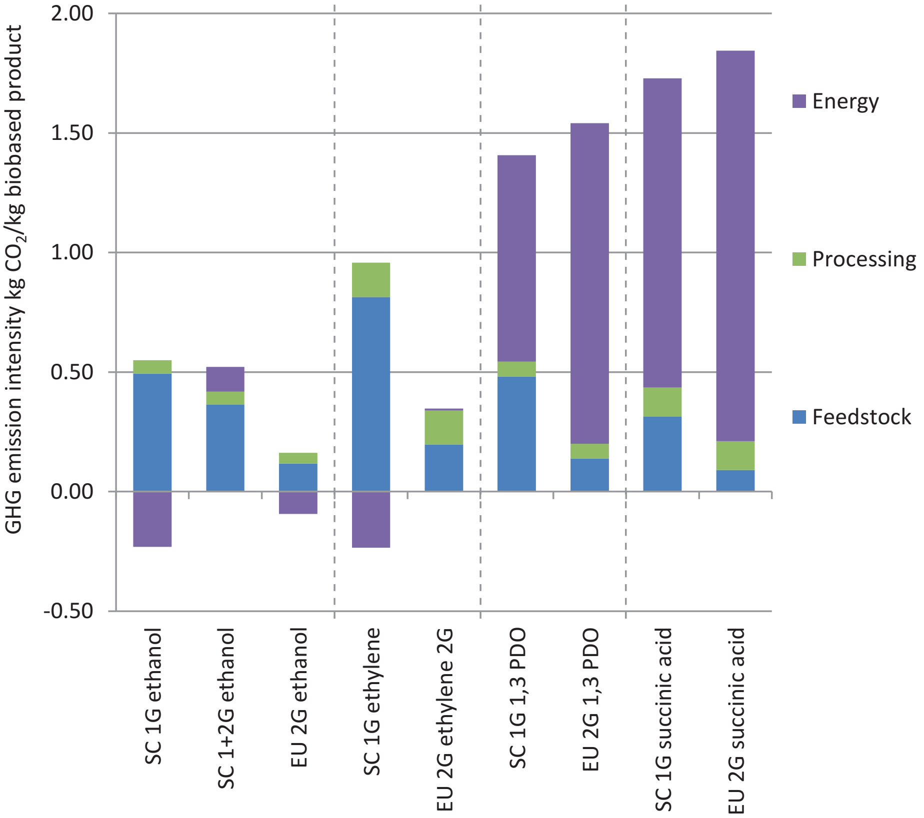

Figure 6-4 Contribution of the different element to the GHG emission intensity of biobased chemical.

6.5.6 Sensitivity analysis for key GHG emission intensity parameters

The results of the sensitivity analysis for the GHG emission intensities, when varying the feedstock GHG emission intensity, BPY and electricity GHG emission intensity are shown in SI.4. For the biobased products the GHG emission intensity is mainly caused by the feedstock supply GHG emissions; a change of the GHG emission intensity of feedstock supply or the BPY has the largest influence on the total GHG emission intensity of these products. Examples are the sugarcane to ethanol (first generation industrial technology) and sugarcane to ethylene production pathways, see Figure 6-4. For industrial pathways, of which the GHG emission intensity is mainly caused by the energy demand, the total GHG emission intensity varies strongly with a variation in energy GHG emission intensity.

6.5.7 Range of GHG emission intensity

The uncertainty range of the GHG emission associated with the production of biobased chemicals are shown in Figure 6-5; as well as the range of fossil gasoline, ethylene, 1,3 PDO and succinic acid equivalent products. For the 1,3 PDO and succinic acid based on sugarcane and eucalyptus, the large range is mainly caused by the variation in the GHG emission intensity of electricity. For ethanol and ethylene, the GHG emissions intensity may even result in a negative GHG emission intensity due to the credited GHG emission of electricity surplus. Overall, the range of GHG emission intensity of the biobased chemicals is predominantly lower compared to the range of GHG emissions of the petrochemical reference.

The GHG emission intensity of ethanol production using sugarcane and eucalyptus feedstock is in the range of -0.08 – 0.72 kg CO_2/kg ethanol. The low values are the results of low GHG emission for biomass supply, high BPY, and credited GHG emissions. Similarly, for ethylene production, the credited GHG emission result in low GHG emission intensities (0.25 – 0.68 kg CO_2/kg ethylene) compared to the petrochemical reference. Note that a large fraction of the petrochemical GHG emission is due to the embedded fossil carbon released during the combustion. For both ethanol as well as ethylene, the use of eucalyptus results in lower GHG emissions compared to sugarcane, due to the high amount of residues available for electricity production. For 1,3 PDO and succinic acid, the upper level of the GHG emission intensity range overlaps with the lower end of the GHG emission intensity of the petrochemical equivalent. Biobased 1,3 PDO and succinic acid have a GHG emission intensity in the range of 1.80 – 3.68 kg CO_2/kg PDO and 2.24 – 4.55 kg CO_2/kg succinic acid respectively. These values are due to the high energy consumption for recovery and purification. This high energy demand cannot be fully covered with the own production of steam and electricity and, therefore, requires the supply of electricity from the grid. The GHG emission associated with electricity consumption is the major fraction of the total GHG emission intensity of biobased 1,3 PDO and succinic acid.

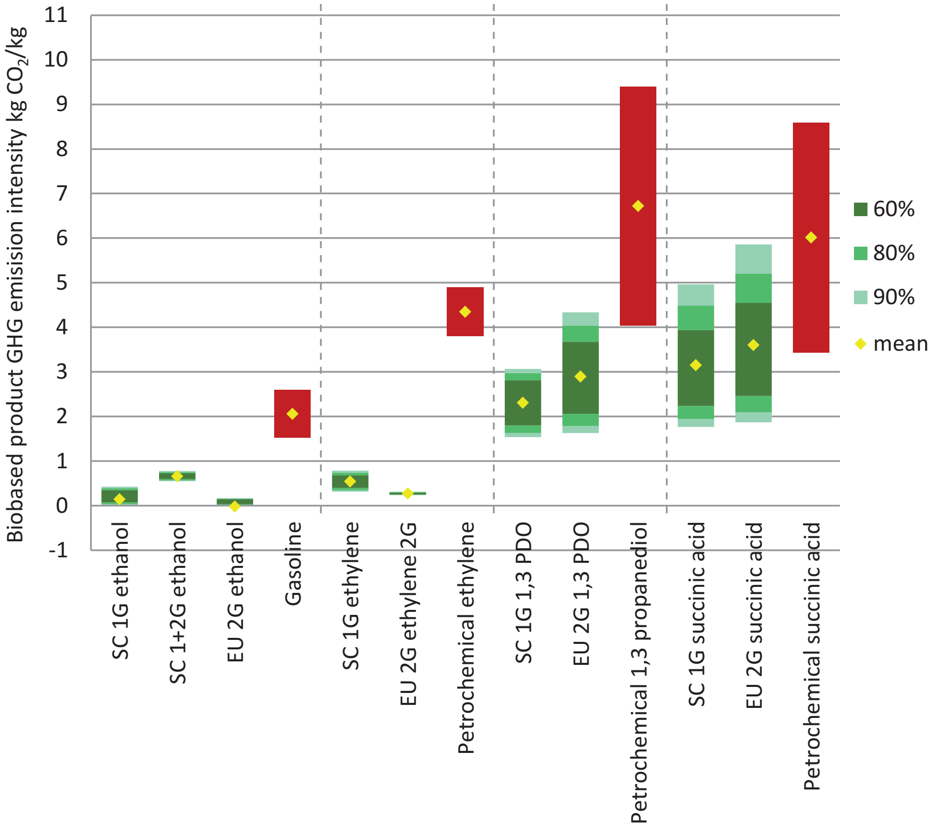

Figure 6-5, Uncertainty range of the GHG emission intensity of the different biobased products and their respective fossil references

6.5.8 Potential profit margin and GHG emission reduction per hectare cultivation area

Figure 6-6 depicts the potential net profit and net GHG emission reduction by sugarcane and eucalyptus production and use in Brazil, expressed in US$/ha-year and Mg CO_2/ha-year for a low or high biomass yield scenario. Figure 6-6 only shows the two base values for potential net profit and net GHG emission reduction. For the GHG emission reduction potential, overall the sugarcane production pathways score better due to the higher biomass yield per hectare, despite the higher BPY of eucalyptus production pathways. All biomass production pathways result in a net GHG emission reduction per hectare, varying between 2 to 17 and 8 to 41 Mg CO_2/ha-year for the low and high yield scenario respectively. At an oil price of 50 US$/bbl, the ethanol and ethylene production pathways have difficulty to compete with the fossil products price, while the production of 1,3 PDO and succinic acid production from sugarcane and the production of succinic acid based on eucalyptus can be profitable. However, the uncertainty in the economic performance, as discussed above, is not considered in this figure.

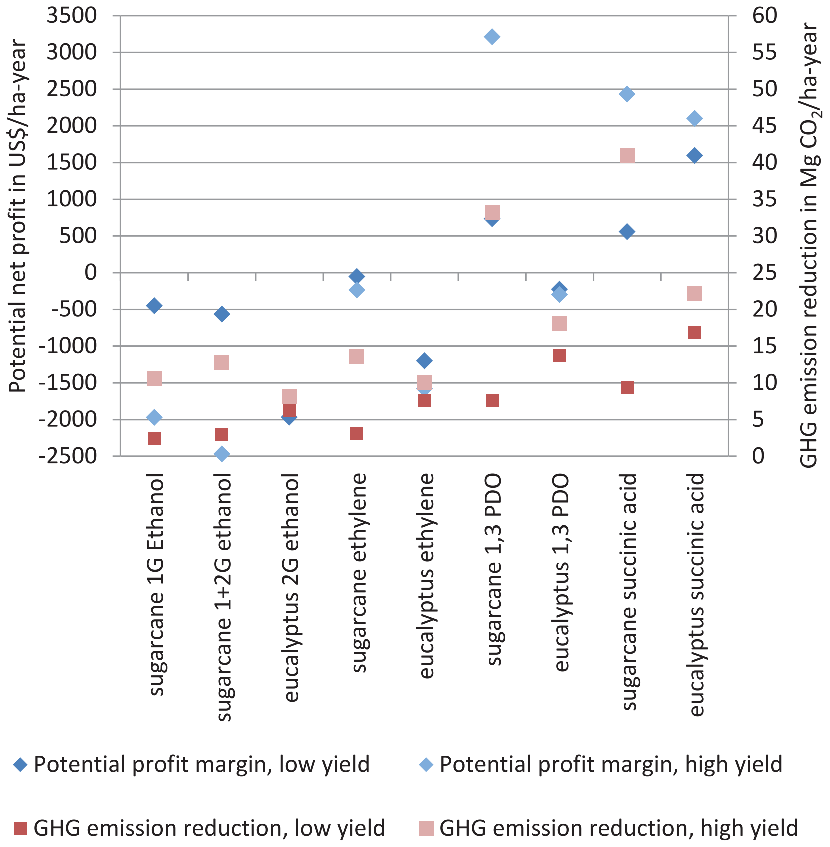

Figure 6-6, Potential net profit and GHG emission reduction per hectare of cultivation area for the different biobased production pathways.

6.6 Discussion

In this study, the production costs and GHG emission intensity of ethanol, ethylene, 1,3 PDO and succinic acid are quantified and compared to the fossil equivalent product. A uniform approach is applied to quantify the production cost ranges (Figure 6-3) and GHG emission intensity ranges (Figure 6-5) for the different biobased production pathways. This uniform approach allows for a harmonized and fair comparison of the production cost and GHG emission performance of the four selected products and industrial pathways. This approach also allows to identify the major contributors to the production costs and GHG emission intensity in a transparent manner. Also the trade-offs between the economic and GHG emission performance can be assessed and enable the selection of the best performing routes in a transparent manner.

However, the since comparison of production costs and GHG emission intensities is based on publically available data, it is not useful to optimize the individual configurations. Also, the current analysis does not include the potential integration or co-production of the selected biobased industrial processing pathways. Furthermore, the considered input values for the GHG emission intensity and costs of electricity and biomass feedstock are based on the current situation. However, with increasing demand the variables and parameters used to determine the economic and GHG performance are likely to change in the future and may shift the ranking of best performing pathways.

The results should be interpreted as ranges rather than single values, given the uncertainties in the biomass supply costs and GHG emission intensity, biobased product yield, total capital investment, and costs and GHG emission intensity of electricity. The ranges are based on the considered ranges and the probability distributions for BPY, biomass feedstock costs, industrial scale, FCI, and GHG emission intensity, and price and GHG emission intensity of process energy demand. For PDO and succinic acid production, the estimated uncertainty is higher than for ethanol and ethylene, due to the limited data available. Note that the assumptions on the range of the different parameters have a higher impact on the range of the final results than the choice of probability distribution of the parameter. Therefore, in this analysis, considerable attention is given to the selected range of the BPY, since it is a key parameter in the quantification of both the production costs and GHG emission intensity of the biobased products. As shown in Table 6-9, the PBYs of all conversion processes used in this study are in line with the ranges found in the literature. Therefore, the considered range of BPY in this study is assumed to be a good indication of the biobased product yield for the selected industrial processing pathways.

Table 6-9 comparison of the BPY of various conversion routes used in this study with values found in literature.

	First generation ethanol using sugarcane	Integrated first-and-second generation ethanol using sugarcane	Second generation ethanol using eucalyptus	Ethanol to ethylene conversion	Production of 1,3 propanediol from sugars	Production of succinic acid from sugars
Unit	kg EtOH/TC	kg EtOH/TC	kg EtOH /tonne EU	kg ETE/kg EtOH	kg PDO/kg sugars	kg SA/kg sugar
This study	57 - 72	79-96	204-268	0.598	0.46	0.78
Literature	60 – 102[A]	78-90[B]	196-297[B]	0.572 - 0.609[C, F]	0.44[D]	0.61[D] - 0.92[F]

[A] (Dias, Cunha, et al., 2011; J.G.G. Jonker, F. van der Hilst, H.M. Junginger, O. Cavalett, M.F. Chagas, 2014; MINISTÉRIO da et al., 2010).
[B] (Macrelli et al., 2012)
[C] (Haro et al., 2013; Liptow & Tillman, 2009; Zhang & Yu, 2013).
[D] (Alves et al., 2016).
[E] (Efe et al., 2013)
[F] These values represent a mass conversion efficiency of 94 to 99%.

The production cost ranges for the biobased chemicals investigated in this study partly overlap with the calculated range of production costs for petrochemical equivalent products. The base values for the biobased products, as reported in Figure 6-3, are higher (ethanol, ethylene and 1,3 PDO from eucalyptus) or lower (1,3 PDO from sugarcane and succinic acid) than the fossil equivalent products, but the differences are small. The variation in petrochemical products is based on a variation in the crude oil price between 40 and 130 US$/bbl. With current oil prices of 50 US$/bbl, most of the biobased production pathways have difficulty to compete, but increasing oil prices can increase the economic viability. The economic assessment in this study does not consider the possible impact of taxes, tax exemptions, or premiums payed for biobased products. As indicated by (Nitzsche et al., 2016), the premium of biobased ethylene can be as high as 30-60% of the price of fossil ethylene. Furthermore, the market price of more complex chemicals highly depends on the purity of the product (Zeikus, Jain, & Elankovan, 1999). All these factors make the determination of the economic viability of the biobased products not straightforward. As the differences in the production costs between the biobased and petrochemical production are small, a variation in either one can change the project viability largely.

As shown in Figure 6-3, the fossil reference prices can vary significantly. Over the past 10 years, the crude oil price varied between 35 and 140 US$/bbl (Haro et al., 2013). For gasoline, this would correspond to an ethanol equivalent price between 0.25 and 1.00 US$/kg. Such fluctuations strongly affect the profitability of biofuels and biochemical. The potential profit margin used in Figure 6-6 is based on the base values (crude oil price about 50 US$/bbl) of the economic quantification. Therefore, an increasing oil price can result in a positive potential net profit for ethanol and ethylene. For example, the largest difference for sugarcane ethylene production is 0.4 US$/kg, this would imply a potential net profit of 1326 US$/ha. On the other hand, the largest negative difference for the production of sugarcane 1,3 PDO is -0.8 US$/kg product, this could mean a potential loss of -4420 US$/ha. When expressing the performance per hectare, the BPY and biomass yield ranges amplify the difference between the production costs of biobased and petrochemical products.

Commonly, the GHG emission intensity of biobased products is lower than the fossil equivalent product. In Table 6-10 the GHG emission reduction of the four selected biobased products are shown, expressed per kg biobased product, or as percentage GHG emission saving, or the GHG emission reduction potential as provided by Jong et al., (2011). The study of Jong et al., (2011) was the sole study found showing the GHG emission reduction of all biobased products considered in the current analysis. With the exception of ethanol and ethylene, the values provided by de Jong et al., (2011) are in the range identified in this study. As the biomass feedstock and biomass supply region were not specified by the study of de Jong et al, (2011), a more detailed comparison is difficult, but this study shows the wide ranges, and thus cautions against the use of single values.

Table 6-10, GHG emission reduction potential of ethanol, ethylene, 1,3 PDO and succinic acid, expressed per kg bobased product, as provided by de Jong et al., (2011) and expressed as percentage GHG saving compared to the fossil reference.

	Ethanol	**Ethylene**	**1,3 PDO**	**Succinic acid**
Absolute GHG reduction (kg CO_2/kg biobased product)	1.28 - 2.17	3.56 - 4.11	2.38 - 5.19	0.15 - 4.25
Absolute GHG reduction (kg CO_2/kg biobased product) (de Jong et al., 2011)	2.7	2.5	5	2.9
Relative GHG reduction (% reduction compared to base value fossil reference)	62 - 105%	82 - 95%	35 - 77%	3 - 71%
GHG emission reduction (Mg CO_2/ha-year)	2 - 13	3 - 14	8 - 33	9 - 41

As shown in Table 6-10, high percentages of GHG emission saving can be achieved with ethanol and ethylene production. The highest absolute GHG emission reduction per kg product can be achieved with 1,3 PDO and succinic acid production, i.e. up to 7.9 and 6.8 kg CO_2/kg biobased product respectively, see Table 6-10. Yet, when the results are expressed per hectare of cultivated area, the highest GHG emission reduction can be achieved with sugarcane succinic acid production; up to 41 Mg CO_2/ha per year. This illustrates that the choice of metric can have a major impact on the ranking of the different industrial pathways.

The range of the GHG emission intensity of the petrochemical products , as discussed in section 6.4.4, considered in this study is large. This variation of the reported values is due to different methodological approaches used, allocation method applied, and case specific characteristics. A detailed assessment of the GHG emissions of petrochemicals was not within the scope of this study. To enable a fair comparison, the approach to quantify the GHG emission (and GHG emission reduction potential) of petrochemical products should be similar to biobased products.

A methodological challenge is the fact that there is no commonly agreed upon method to quantify the GHG emission intensity for chemicals such as PDO or succinic acid. For gasoline, the fossil reference is well-known and defined to determine the GHG emission reduction of biofuels for transport, (European commission, 2012; Soratana et al., 2014). However, for chemicals from fossil feedstock, no commonly agreed methods to determine reference values exist; despite the fact that these chemicals are typically already produced for years. The range of potential fossil GHG emission adds another source of uncertainty of the potential emission reduction of biobased chemicals.

Finally, it is important to note that for the GHG emission reduction per hectare, no land-use change GHG emissions ware taken into account in this study. Based on the study of Jonker et al., (2016), direct land-use change GHG emissions in the state of Goiás can be as high as 462 kg CO_2/TC and 1571 kg CO_2/tonne eucalyptus. This could potentially mean additional GHG emissions as high as 3.8 and 4.0 kg CO_2/kg succinic acid for sugarcane and eucalyptus respectively, using the high-end BPY for succinic acid production as shown in Table 6-8. Such high direct land-use change GHG emissions can reduce the GHG emission reduction potential completely. However, land-use change GHG emissions per tonne of biomass feedstock can also be zero or positive, and should therefore be included in future assessments. Similarly, the indirect land-use change GHG emissions can also have a negative, no or positive impact on the GHG emission intensity per hectare.

6.7 Conclusions

The aim of this study was to uniformly quantify the production costs and GHG emission intensity of ethanol, ethylene, 1,3 PDO and succinic acid from sugarcane and eucalyptus feedstock. This assessment enables a comparison of biobased products to its fossil equivalent product and a comparison between different biobased industrial processing pathways. Due to the uncertainty associated with the biobased product the results are presented in ranges. These ranges become larger with increasing uncertainty and lack of data, especially true for the less conventional biobased chemicals.

The reported ranges of the biobased production costs partly overlap with the ranges of the fossil reference products. This analysis shows that sugarcane based 1,3 PDO, and to a lesser extent the production of succinic acid, result in the best economic viability.

However, the costs of these production pathways are more uncertain compared to ethanol and ethylene production. As the differences between the biobased production costs and fossil equivalent product costs are small, the net profit, expressed per kg product or per hectare of cultivation area is highly depended on this difference. With an increasing oil price more biobased production pathways can become economically viable in the future.

The GHG emission of petrochemical ethanol and ethylene is largely due to the embedded carbon in fossil equivalent products. Therefore, the GHG emission reduction of ethylene is relatively certain between 3.5 and 4.7 kg CO_2/kg ethylene produced. The GHG emission intensity of other fossil reference products depend more on the GHG emissions in the supply chain, especially the energy demand and subsequent GHG emissions. Considering the potential GHG emission reduction and potential profit per hectare, the industrial processing pathways utilizing sugarcane score better than eucalyptus feedstock due to the high yield of sugarcane specifically in Brazil. It was not possible to choose a clear winner, as a) the best-performing product strongly depend on the chosen metric (percent GHG emission reduction, absolute GHG emission reduction per kg biobased product, or GHG emission reduction per hectare of land), and b) the large ranges found especially for PDO and succinic acid, independent of the metric.

As indicated, the BPY, FCI, and energy consumption of different biobased production pathways are important for the economic and GHG emission performance. However, these key variables are not always well documented for each process-step of all industrial pathways. Therefore, key topics calling for further research are: Firstly, quantification of the conversion efficiencies of large-scale industrial processing facilities for biobased chemicals, especially for more complex biobased chemicals. Secondly, detailed analysis of equipment costs, scaling factors, maximum scale and total investment cost of the different industrial processing steps. Thirdly, more insight in the inputs and especially the energy consumption of new industrial processes for the fermentation and recovery of novel biobased products. This also includes industrial pathways with multiple main products and more complex biorefinery concepts. Next to improving the data quality and availability of the biobased pathways, also more data is required regarding the fossil equivalent products, and their production costs and GHG emission intensity. This study has quantified the GHG emission intensity and production costs of biobased ethanol, ethylene, 1,3 PDO and succinic acid. To consider the overall sustainability of biobased fuels and chemicals, more aspects should be assessed, including land-use change GHG emissions, impact on water and biodiversity and socio-economic aspects.

The approach applied in this study can be applied to more biobased production pathways; utilization of different biomass feedstock or for the production of different biobased products. The publication of uniform comparisons of the economic and GHG emission performance of different biobased production pathways can provide direction to reduce more GHG emissions with biomass use or make an economically attractive business case.

Acknowledgement

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Supplementary information

6-SI.1. Process descriptions

The industrial process of first generation ethanol production includes sugarcane washing, followed by shredding and milling to extract a sugar-rich juice. After juice treatment the juice is fermented to an ethanol-rich broth, CO2 and coproducts like higher alcohols, organic acids, etc.. After the broth went through a distillation column and a rectification column to produce hydrous ethanol, further dehydration yields anhydrous ethanol (38). The available sugarcane bagasse (after extraction of the juice) and potentially trash (residue of sugarcane harvesting) is used in the cogeneration unit for the production of the process steam and electricity demand. Most Brazilian sugarcane mills have an excess electricity production which can be fed to the electricity grid to reduce ethanol production costs (22).

Large scale production of ethylene from ethanol includes mixing ethanol with water (1:1 molar ratio), after which it enters the dehydration reactor with increased pressure and temperature (340°C and 5 bar). After dehydration the flow is cooled and compressed before dewatering and conditioning for the recovery of ethylene. The ethylene gas passes two fractionation columns for the removal of unwanted coproducts. coproducts are combusted together with natural gas for heat production. The ethylene stream has a product purity of 99.99% on weight basis (21).

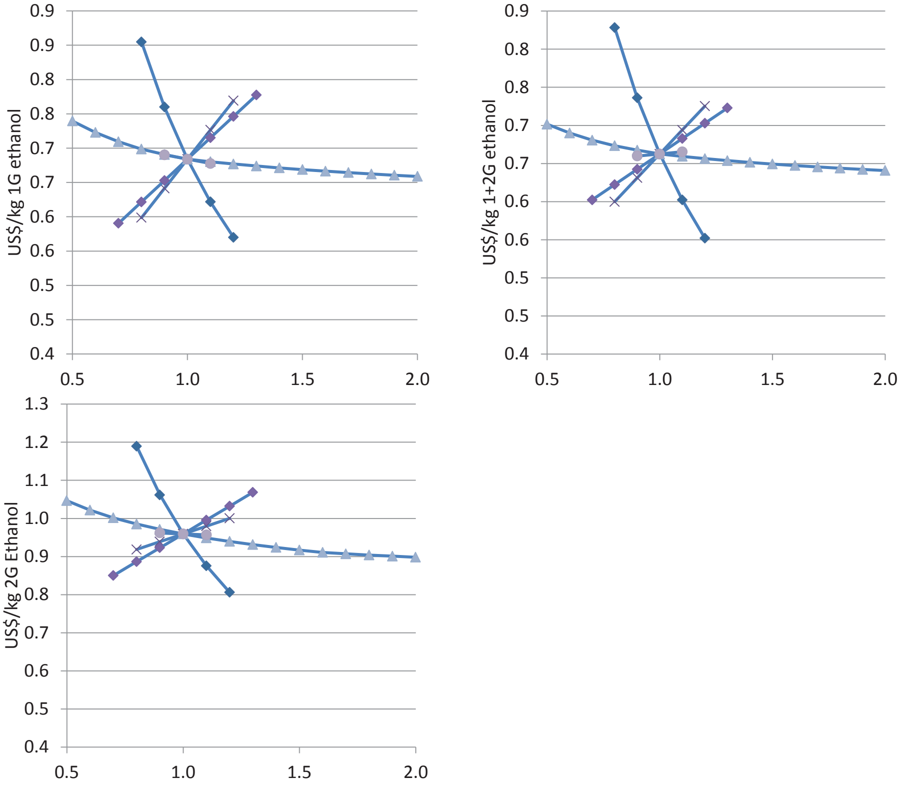
The production of 1,3 PDO includes the sugar extraction similar to the ethanol production process, followed by PDO production by a genetically engineered organism. After sterilization, the fermentation broth passes a centrifuge and continuous through a dewatering columns and finally a train of distillation columns (66).

The industrial process from sugarcane to succinic acid includes sugar extraction, followed by fermentation, and thereafter centrifugation to remove cell mass, the broth is then fed to adsorption columns, followed by desorption columns and a flash drum. After storage to enable continuous processing the liquid is concentrated by evaporating followed by a crystallizer, the crystals are removed by a vacuum filter (16).

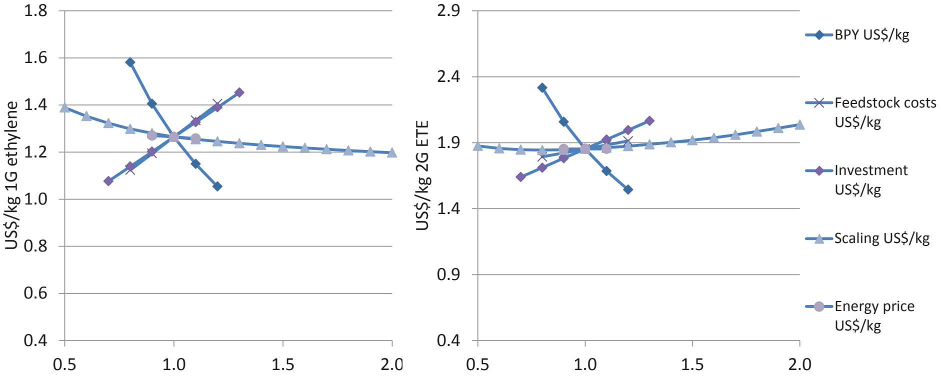
6-SI.2. Assumptions for uniform comparison

Parameter	**Value and unit**
Operational hours first generation industrial processing facility	4080 hours/year
Operational hours second generation industrial processing facility	8000 hours/year
Annuity	0.12
Annual maintenance costs	2% of TCI
Annual labour costs	3% of TCI
Annual operational costs	0.75% of TCI
Boiler efficiency	90%
Moisture content residues	50%

6-SI.3. Sensitivity analysis for biobased production costs



Sensitivity analysis for ethanol production costs via first generation, second generation and integrated first-and-second generation industrial processing of sugarcane and eucalyptus



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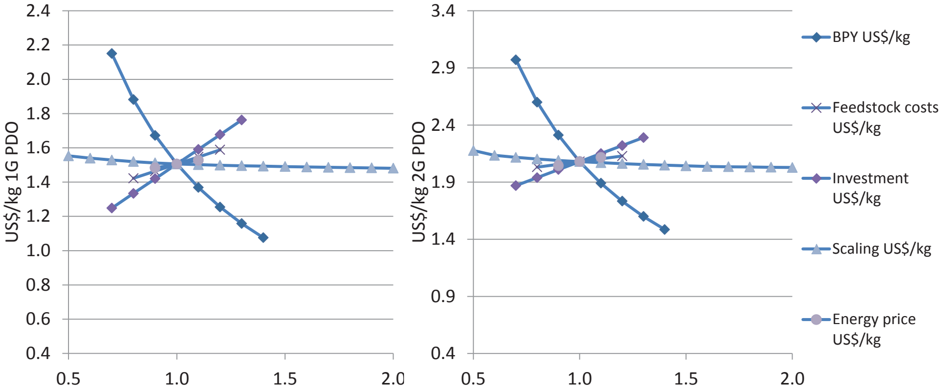
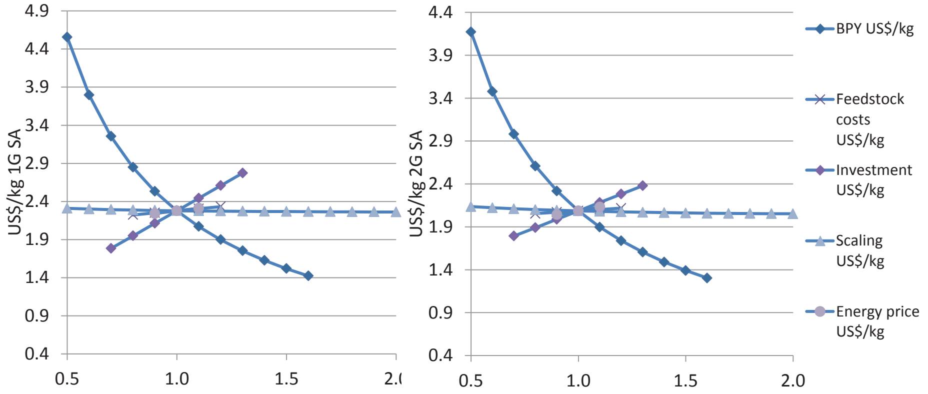
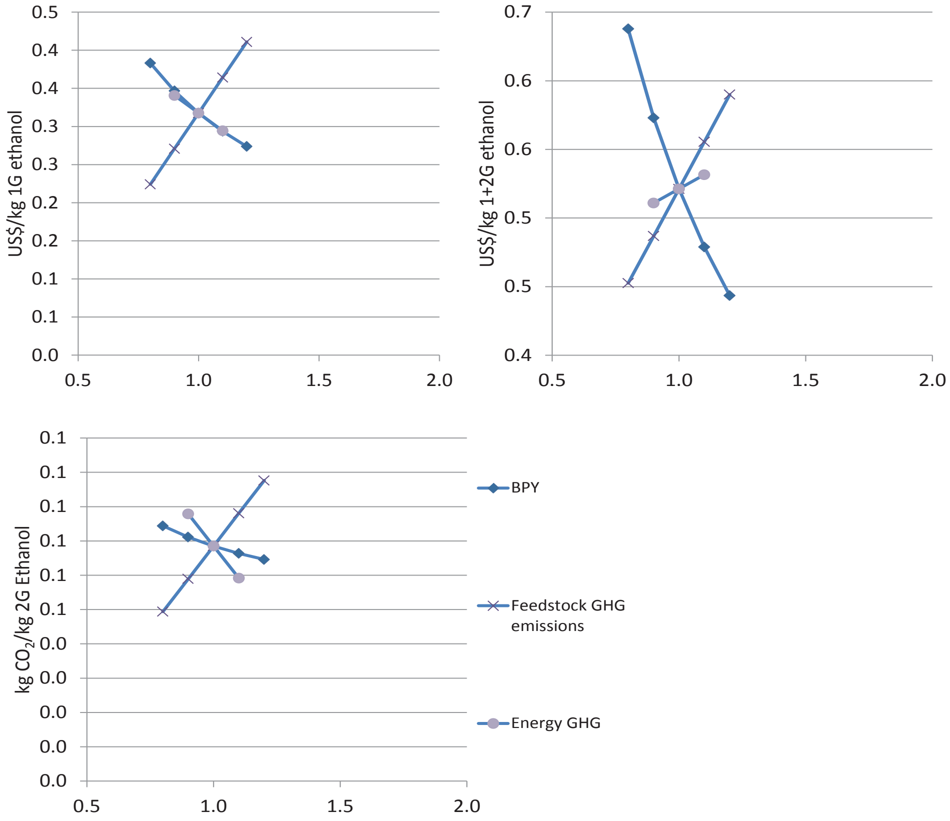


Sensitivity analysis for 1,3 PDO production costs via first generation and second generation industrial processing of sugarcane and eucalyptus.

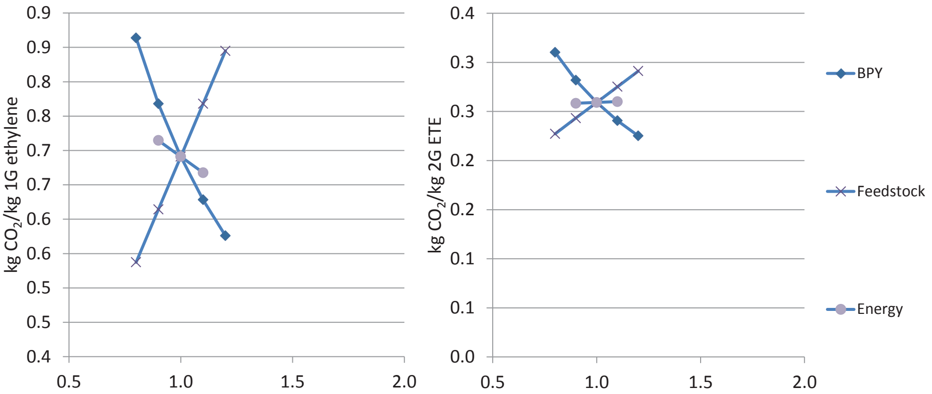


Sensitivity analysis for succinic acid production costs via first generation and second generation industrial processing of sugarcane and eucalyptus.

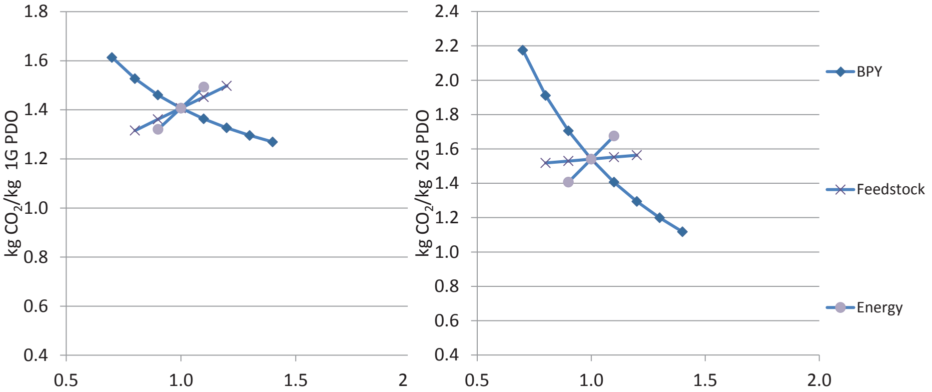
6-SI.4. Sensitivity analysis for GHG emission intensity



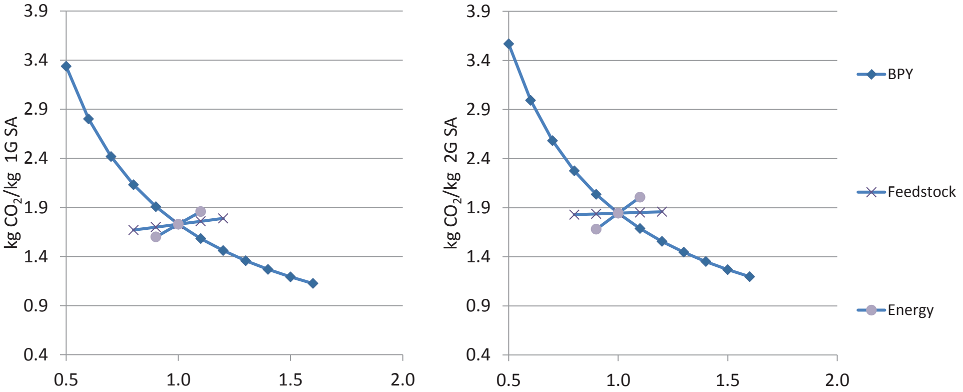
Sensitivity analysis for ethanol production costs via first generation, second generation and integrated first-and-second generation industrial processing of sugarcane and eucalyptus



Sensitivity analysis for ethylene production costs via first generation and second generation industrial processing of sugarcane and eucalyptus.



Sensitivity analysis for 1,3 PDO production costs via first generation and second generation industrial processing of sugarcane and eucalyptus.



Sensitivity analysis for succinic acid production costs via first generation and second generation industrial processing of sugarcane and eucalyptus.

Chapter 7

Synthesis, conclusions and recommendations

7.1 Background and research context

There is a widespread scientific consensus that global climate change is with high levels of certainty caused by the increased levels of anthropogenic greenhouse gasses (GHG) in the atmosphere (IPCC, 2014b). Continued emission of GHGs eventually lead to irreversible and severe impact on people and ecosystems. Therefore, *substantial and* sustained anthropogenic GHG emission reductions are necessary to limit the impact of climate change (IPCC, 2014b). Biomass cultivation and utilisation for the production of electricity, biofuels and chemicals is seen as an important GHG mitigation option (H. Chum et al., 2011; IPCC, 2014b). An increasing demand for biomass would inherently require an increase in supply. However, there is uncertainty regarding the biomass supply potential in the future. The biomass supply potential for 2050 differs by up to three orders of magnitude in size (IPCC, 2014a). The review of (Creutzig et al., 2015) qualified the sustainable biomass supply ranges according to their agreement among scientists; up to 100 EJ_{PRIM}/year in 2050 reached high agreement, while the range of 100-300 EJ_{PRIM}/year is qualified as medium agreement (Creutzig et al., 2015). Given that the biomass supply is limited, it is important to exploit its potential as GHG mitigation option effectively.

Biomass utilization will not by default generate a GHG emission reduction compared to the fossil reference. The GHG emission reduction potential has recently been questioned with the inclusion of carbon stock change in the total GHG balance (Cherubini, Guest, & Stromman, 2013; T. D. Searchinger, 2009). To quantify and compare the GHG performance of biomass supply chains, the GHG balance should include both supply chain and LUC related GHG emissions. The GHG balance is influenced by the GHG accounting method, as well as by e.g. the biomass feedstock selection, plantation management, biomass yield and selection of conversion technology. These characteristics are site- and case study specific, and change over time. Therefore, the GHG balance of current and future biomass supply chains should be quantified with a uniform approach while taking into account region and case-specific parameters and data.

The economic viability of biomass use is an important driver for large-scale utilization. The production of biobased electricity, fuels and chemicals should be able to compete economically with fossil equivalents. To enable a transparent comparison between the economic performance of different biomass supply chains the use of a uniform approach, with the use of similar economic assumptions, scale, etc., is required. To determine the costs for biomass deployment, and the subsequent substitution of fossil resources, a comparable unit of analysis should be chosen. Uniform, harmonized economic assessments to quantify and compare the economic performance of different biomass supply chains are however not agreed upon in literature.

Based on the knowledge gaps in existing literature, important topics for research are: 1) The methods used for the quantification of the economic performance and GHG emission reduction potential of biomass use, 2) Regional specific case studies for the economic performance and GHG emissions of large-scale production of electricity, fuels and chemicals. Furthermore, a detailed quantification of the economic performance and GHG balance can also show the possible trade-off between these key indicators.

Two very important biomass production systems today, are the wood pellet production in the Southeastern USA, mainly for overseas electricity production, and the sugarcane - ethanol production in Brazil. These regions are key biomass producers and make a significant contribution to the global bioenergy supply. Both production regions have the potential to significantly expand their production in the coming decades, by the expansion of the cultivation area, improvements in agricultural or industrial yield and the introduction of new industrial processing pathways and value chains.

7.2 Research questions and outline of the dissertation

The aim of this thesis is to assess, combine, and harmonize different methods to uniformly quantify and compare the GHG emissions and economic performance of regional specific biomass supply chains. To this end, the following research questions are addressed:

3 How to uniformly quantify the total GHG balance of biobased supply chains for the production of electricity, fuels and chemicals, and what are the GHG emission balances for specific regional case studies?

4 How to uniformly quantify the economic performance of biobased supply chains for the production of electricity, fuels and chemicals, and what is the economic performance of specific regional case studies?

5 What are the trade-offs between the GHG balance and economic performance of different biobased supply chains for different regions?

In answering these questions, different biomass supply chains for the production of electricity, fuels and chemicals are assessed. These supply chains cover different biomass crops, plantation management strategies, harvest technologies, industrial processing technologies and final products. See Table 7-1 for an overview of the different chapters, and the addressed research questions. It is followed by the answers to the 3 main research questions of this dissertation.

Table 7-1.

Chapters		Research question 1	2	3
2	Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States	x		
3	Carbon balances and economic performance of pine plantations for bioenergy production in the Southeastern United States	x	x	x
4	Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies		x	
5	Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil	x	x	x
6	Economic performance and GHG emission intensity of sugarcane and eucalyptus derived biofuels and biobased chemicals in Brazil.	x	x	x

7.3 Answers to the research questions.

<u>How to uniformly quantify the total GHG balance of biobased supply chains for the production of electricity, fuels and chemicals, and what are the GHG emission balances for specific regional case studies?</u>

In this dissertation three key aspects of the GHG balance of biobased supply chains are discussed in detail: the first is the GHG emission during cultivation, transport and processing to biobased products. The second aspect is the carbon stock change associated with forest biomass supply. The third aspect are the GHG emission related to land-use change for biomass crop production. The findings of this dissertation regarding these three aspects and their performance are discussed in detail below.

Supply chains GHG emissions

The GHG emissions of cultivation, transport and industrial processing are quantified for softwood biomass in the Southeastern USA (chapter 2&3), ethanol production in the state of Goiás (chapter 5) and different biobased products, including ethanol (chapter 6).

In chapter 2&3 the GHG emissions of the cultivation, harvesting, transport, processing and final product use are quantified as part of the overall carbon balance. This carbon balance considers the GHG emissions of plantation management, harvest and transport, carbon in live and dead trees, embedded carbon in final wood products, and displaced carbon due to product substitution. The GHG emissions of plantation management are determined based on the use of fertilizers, consumption of agrochemicals and the diesel use of different silvicultural practices. For chapter 2 the GHG emission are considered for whole-tree harvesting and expressed per tonne wood pellets delivered. The total GHG emissions are between 355 and 420 kg CO_2/tonne pellets. Silvicultural GHG emission for the low-, medium- and high productive strategies cause the difference. For chapter 3, the total GHG emissions are economically allocated to the different wood classes harvested. Taking into account the harvesting, collection and transport GHG emissions to the cultivation GHG emissions, results in the total delivery GHG emissions of pulpwood size wood or slash wood. GHG emission associated with the plantation management (excluding harvesting) of softwood plantations in the Southeastern USA are between 3.7 – 7.2 kg CO_2/Mg dry pulpwood cultivated. Taking into account harvesting and transport, the total GHG emissions for wood supply to industrial processing facilities amounts 27 up to 33 kg CO_2/Mg dry pulpwood. To account for the GHG emissions or GHG emission reduction in the remainder of the supply chain and the utilization phase, the harvested wood is categorised into four different wood product categories (long, medium-long, medium short and short life wood products), each with a specific displacement factor. The carbon displacement factor represents the carbon efficiency of wood product use compared to the use of other materials and quantifies the amount of GHG emissions avoided, following the definition of (Sathre & Connor, 2010). In other words; this aggregated factor expresses the GHG emissions of wood use compared to the use of alternative products. The displacement factor the different wood classes is 2.1, 1.8, 1.5 and 0.5 for the wood classes sawtimber, chip-n-saw, pulpwood and slash respectively.

In chapter 6, the total GHG emission intensity of different biobased products is determined. GHG emissions of biomass cultivation and transport are included through use of data published in other studies for sugarcane and eucalyptus cultivation and transport. The mass and energy inventory was used to determine the biobased product yield and the GHG emissions, expressed in kg CO_2 per kg biobased product at the factory gate. GHG emissions include the feedstock supply, industrial processing emissions and the GHG emissions associated with the additional steam, heat and electricity demand. The total GHG emission intensity of ethanol production using sugarcane and eucalyptus feedstock is in the range of -0.08 – 0.72 kg CO_2/kg ethanol. Similarly, for ethylene production, the credited GHG emission result in low GHG emission intensities (0.25 – 0.68 kg CO_2/kg ethylene) compared to the petrochemical reference. Biobased 1,3 PDO and succinic acid have a GHG emission intensity in the range of 1.80 – 3.68 kg CO_2/kg PDO and 2.24 – 4.55 kg CO_2/kg succinic acid respectively.

The supply chain GHG emissions quantified in this thesis are expressed in different units. However, the choice of the unit is considered as the most appropriate for the comparison made in the individual case studies.

Forest biomass carbon accounting

The carbon stock change of forestry biomass is analysed through use of the dynamic carbon balance approach; an overview of all carbon pools and their change over time. This carbon balance is the sum of the in-situ (carbon in live trees, decaying carbon in dead trees and harvest residues) and ex-situ (embedded biogenic carbon in harvested wood products and displaced fossil carbon due to product displacement) carbon pools (Chapter 3). In chapter 2, the GORCAM carbon accounting model is utilized to determine carbon stocks and stock changes of forest carbon in softwood plantations in the South-eastern United States. While chapter 3 zooms in on the impact of plantation management strategies and determines the impact of the management strategies on individual tree volume and number of live trees to determine the total wood volume per hectare at each year of the rotation period. The volume growth curve of loblolly pine trees and the harvested wood classes are key input to allocate plantation management GHG emissions, and to calculate the in-situ and ex-situ carbon pools (Chapter 3).

As discussed in chapter 2, important aspects that have on impact on the carbon balances are yield, carbon replacement factors, system boundaries and the choice of reference scenario used to determine the parity point. Each of these four aspects is discussed more elaborately below:

Chapter 2 points out that switching to highly productive plantations increases the uptake of carbon strongly, which offsets the additional emissions of silvicultural practices by far. Increased silvicultural emissions are compensated by faster (re) growth of plantations, and thereby increased uptake of carbon and increased fossil fuel displacement after harvest. Comparing the GHG emission in the supply chain to the avoided fossil fuels the low yield plantation management strategy has emitted 30 Mg carbon/ha after 75 years while the accumulated avoided GHG emissions are 188 Mg carbon/ha. For the high productive strategy these values are 73 Mg carbon/ha and 339 Mg carbon/ha for supply chain and avoided GHG emission respectively. In chapter 3, the impact of plantation management strategies on tree growth and growth rate is assessed. The key variable in the tree growth simulation is the diameter growth, as it is the key parameter for tree volume and product volume classification. Although the diameter growth parametrization is based on a somewhat older study (Pienaar et al., n.d.), a more recent analysis of (Zhao et al., 2011) showed a similar diameter growth curve as simulated in the current analysis. However, the parametrization of the growth equations used for this study were based on empirical data for lower planting densities. To model higher planting densities, more empirical data to enable better parametrization would be desirable. Based on Chapter 3, it can be concluded that the total wood volume yield is not per se the best criterion for the selection of plantation management strategies to accumulate carbon. For example, the wood yield of the short rotation management strategy is high, however, it yields mainly pulpwood quality material, which has a lower displacement factor (Table 3-6, Chapter 3). Considering the difference between the conventional and the additional thinning strategy; the additional thinning strategy produces more pulpwood, while the amount of sawtimber and chip-n-saw wood is equal in both strategies. So, the addition pulpwood yields results in a higher displacement of fossil carbon as it does not affect the wood yield of other wood classes. The high pulpwood yield in the short rotation management strategy does not compensate for the reduced carbon displacement factors for pulpwood compared to sawtimber.

Especially for simulation periods of 100 years and longer, the carbon balance is dictated by the carbon displacement due to product substitution, in contrast to the stabilizing biogenic carbon embedded in wood products. The study of (Perez-Garcia et al., 2006) also illustrated the high share of displaced carbon in the overall carbon balance, especially over longer time periods. As wood pellets directly replace coal in chapter 2, a 0.92 replacement factor (tonne carbon avoided per tonne carbon harvested) seems justified. The main issue with the use of generic carbon displacement factors is the lack of data regarding wood processing, utilization of wood products, product lifespan and end-of-life disposal of wood products (Brunet-Navarro et al., 2016). Including the carbon displacement factors shows the impact of different wood class yields outside the forest plantation. Therefore, it provides a better picture of the impact of plantation management decisions on the overall carbon balance. Finally, it is also debatable whether the carbon displacement factors should be kept constant for the coming 100 years. Due to product and technology development, the GHG emission intensity of wood products or the alternative product can change.

The choice of methodological approach has a large impact on the calculation of carbon payback period or carbon offset parity point (chapter 2). The result of Chapter 2 with respect to the carbon balances clearly demonstrate that the choice of carbon accounting method has a significant impact on the carbon payback periods and carbon offset parity periods determined. In Chapter 2 the stand-level (static system boundary), increasing stand-level (dynamic system boundary) and landscape approach (static system boundary) is used. As also indicated by (Sintas 2017), the choice for the methodological approach very much depends on its purpose. We consider the landscape-level carbon debt approach more appropriate for the situation in the South-eastern United States, where softwood plantations are common practice. However, for the objectives defined in Chapter 3; quantify the impact of plantation management strategies on carbon balance, the use of the stand-level approach is justified.

Finally, chapter 2 points out that in our case study, the choice of ‘no-harvest’ as reference scenario for the parity offset point calculations is not straightforward. From interviews with forest experts in South-eastern United States, we consider ‘no-harvest’ and ‘natural regrowth’ scenarios as not realistic; without financial compensation it is likely that plantations that are not harvested for timber/ fibre would be converted into, for example, urban development or agricultural land. In such a case, no or significantly less carbon would be fixed in the reference scenario, which would then most likely be far worse than any bioenergy scenario.

The results of chapter 2 show that the carbon payback period of a single stand, using the stand-level approach, varies between 5 and 11 years, depending on the management intensity scenario. For the carbon offset parity point, using the increasing stand-level approach, the productive scenarios are preferred after 17–39 years. For the landscape approach, the range is even wider: from a 46 years carbon offset parity period in the worst case, to a mere 12 years for a high-intensity scenario. When only looking at the carbon debt at landscape level, the time spans to reach break-even point become negligible, i.e. shorter than 1 year. However, most other studies (Walker et al., 2010; Zanchi et al., 2010; Colnes et al., 2012; Mitchell et al., 2012) use the carbon offset parity point method. When comparing our results with these studies, we find that the carbon offset parity point is reached after 17, 22 and 39 years for the increasing stand-level approach. Applying the landscape approach, the carbon offset parity point is reached after 12, 27 and 46 years, for the high-, medium- and low-productive scenario. These times are shorter than the time spans identified by the studies cited above, which find carbon payback periods of <1 year for wood pellet production on former agricultural land (Zanchi et al., 2010; Mitchell et al., 2012), between 16 and 90 years on forested land (Walker et al., 2010; McKechnie et al., 2011) and 19 to 1000 years for old-growth forests (Zanchi et al., 2010; Mitchell et al., 2012).

When zooming in on the impact of plantation management strategies on the carbon balance, as shown in chapter 3, the total carbon stock after 100 years are 205 (247), 214 (268) and 149 (195) Mg carbon/ha for the conventional, additional thinning and short rotation management strategies (in the parentheses is the same strategies with slash). However, when considering the average linear carbon trend line the carbon stock is 213 (244), 216 (259) and 194 (242) Mg carbon/ha for the conventional, additional thinning and short rotation loblolly pine plantation management strategies respectively. Because of the classification of harvested wood to the different wood classes, each with a specific carbon displacement factor, the accumulated displaced carbon is to a large extent determine by the yield of sawtimber and chip-n-saw class wood. It is important to note that the results are specific for loblolly pine stands in the Southeastern USA, and may vary according to regional differences.

Land-use change GHG emission associated with land-use change

Key aspects to quantify the GHG emissions associated with land-use change are the distribution of biomass supply regions; their former and current carbon stock, biomass yield and industrial conversion options following the crop cultivation.

The potential distribution of biomass supply areas is an important element in optimization the entire biomass value chain. This is done for the state of Goiás in Brazil, as shown in chapter 5, and spatially explicit biomass production maps are provided by the land use change model PLUC. By using PLUC, the predefined biomass supply regions, potential locations of new industrial processing plants, the transport distance between supply regions and processing plants, and the land use change emissions can be quantified. It is important to note that the economic objective approach in the optimization model is the driver for the selection of number and location of plants (reduce transport costs) and sizing (reduce capital costs) of industrial plants. Therefore, this analysis shows only the potential GHG emission intensity when using an economic optimization objective with already fixed biomass supply regions. An optimization of the GHG emission intensity of ethanol production in Goiás is not performed in chapter 5.

The agro-ecological suitability (spatially heterogeneous) and maximum yield value (time variable) jointly determine the biomass yield in the supply regions. The combination of the distribution of biomass supply regions and the varying yields of the supply regions is an important feature of this study and results in the spatial heterogeneous biomass availability.

The GHG emission intensity of ethanol production using the economically optimal supply chain designs is dominated by the direct land use change emissions. It is important to note that only the direct land-use change emissions are taken into account, the potential indirect land-use change GHG emissions are not quantified. Potential GHG emissions of indirect land use change depend strongly on the development of the larger agricultural sector and governance of land use and can subsequently be substantial or minimal. Determining those land uses and GHG emissions effects requires a different approach.

Utilizing all the predefined sugarcane and eucalyptus supply regions up to 2030, the results showed that on average the GHG emission intensity of sugarcane cultivation and processing is -80 kg CO_2/m^3, while eucalyptus GHG emission intensity is 1300 kg CO_2/m^3. This is due to the high proportion of forest land that is expected to be converted to eucalyptus plantations. High carbon stock of eucalyptus plantations compared to cropland or pasture combined with high ethanol yield result in high avoided GHG emissions of eucalyptus processing in the range of -3220 and 0 kg CO_2/m^3 ethanol. In contrast, the initial carbon stock of forested land causes high GHG emission intensities of ethanol produced from eucalyptus cultivation on former forested land ranging between 3.1 and 5.9 Mg CO_2/m^3 ethanol. Therefore, on average, the GHG emission intensity of ethanol production utilizing eucalyptus in Goiás is 1300 kg CO_2/m^3 ethanol, only about 30% lower than the fossil fuel based reference (Chapter 5). Conversion of agricultural land results in negative GHG emissions, ranging between -570 and -100 kg CO_2/m^3 ethanol, as the carbon stock of sugarcane plantation is higher compared to the carbon stock of agricultural land (however, no indirect land-use effects have been taken into account). The conversion of pastures results in modest GHG emissions, 205–880 kg CO_2/m^3 ethanol, and the conversion of forested land results in high GHG emissions, ranging between 3150 and 5780 kg CO_2/m^3 ethanol, and thus performs far worse than fossil gasoline. Due to high amounts of cropland being converted to sugarcane plantations, the average GHG emission intensity of ethanol produced in Goiás is -80 kg CO_2/m^3 ethanol in contrast to the fossil fuel competitor of 1800 kg CO_2/m^3 (Chapter 5). The direct land-use change GHG emissions are calculated using a 20 year carbon depreciation period. In other words, the carbon payback period is fixed, the annual carbon stock change is included in the GHG emission intensity. This would imply that after 20 years the land-use change emissions are zero.

How to uniformly quantify the economic performance of biobased supply chains for the production of electricity, fuels and chemicals, and what are the economic performances of region specific supply chains?

To account for the year to year fluctuations in costs and benefits of a biomass plantation and the operation of an industrial plant the *net present value* (NPV) approach is commonly applied for. With the use of a spreadsheet based model, the economic performance of different plantation management strategies (chapter 3), ethanol production pathways using different biomass crops (chapter 4) and different industrial processing pathways for sugarcane and eucalyptus processing (chapter 6) are determined. The economic results of chapter 4 are a key input for the supply chain optimization performed in chapter 5.

The wood supply costs, as quantified in chapter 3, include the plantation management costs (cultivation), harvest and transport to an industrial facility. The plantation management costs of loblolly pine plantations are determined for each year in the plantation management cycle, for three plantation management strategies (conventional, additional thinning, short rotation). The plantation management costs are allocated according to the potential prices of the distinguished wood classes; sawtimber, chip-n-saw, pulpwood and slash. The results show that the use of the conventional strategy results in the lowest wood supply costs, 47 (46) US$/dry Mg pulpwood, for bioenergy;, shortly followed by the additional thinning strategy, 50 (49) US$/Mg pulpwoodThe use of the short rotation management strategy has significant higher wood supply costs, 54 (52) US$/Mg pulpwood with between brackets the cost with the use of slash). The delivery costs of pulpwood can be broken down into cost of land (17-22%), plantation management (15-22%), harvesting (25-31%) and transport (31-37%).

Chapter 4 calculated the bottom-up current and future cost structure of ethanol production given the technical and economic development of biomass feedstock cultivation and industrial processing of first and second generation technologies. The costs include the costs of feedstock cultivation, transport and industrial processing to ethanol. The biomass feedstocks included in this study are sugar cane, energycane, sweet sorghum, elephant grass, and eucalyptus. The development in total ethanol production costs (expressed in US$$_{2010}$/m^3 ethanol) of different configurations is determined (combination of biomass feedstock and industrial processing technology). The results show that sugarcane and energycane cultivation costs could be reduced from 35 US$$_{2010}$/TC in 2010 to 27 US$$_{2010}$/TC and 22 US$$_{2010}$/TC in 2030 respectively. Eucalyptus and elephant grass cultivation costs could be reduced from 32 to 23 US$$_{2010}$/tonne wet and 38 to 26 US$$_{2010}$/tonne wet for eucalyptus and elephant grass. First generation ethanol production costs could decrease by reduced feedstock costs, increase in sugar content, utilization of cane trash, and the use of sweet sorghum. Furthermore, the improvement in industrial efficiency of the first generation process, increasing industrial scale and change to an improved technology are other measures to reduce the production costs. Total ethanol production costs of first generation processing could decrease from 700 US$$_{2010}$/m^3 in 2010, to 432 US$$_{2010}$/m^3 in 2030. For second generation technology utilizing eucalyptus, the total ethanol production costs could be strongly reduced to 424 US$$_{2010}$/m^3 in 2030. Costs reduction measures for second generation industrial processing include reduced feedstock costs, increasing industrial efficiency and scale, and a change to more advanced industrial process.

In chapter 5, the expected expansion of the ethanol processing facilities in Goiás was economically optimised. The BioScope optimization model is used to determine the optimal location and scale of sugarcane and eucalyptus industrial processing plants given the projected spatial distribution of the expansion of biomass production in the state of

Goiás between 2012 and 2030. The overall modelling objective function is to minimize the overall ethanol production costs for all biomass supply regions in Goiás. This objective includes the costs of land, biomass cultivation, biomass transport, and industrial processing. The industrial processing costs include potential revenues of electricity surplus. The data regarding the biomass availability in the biomass supply regions, the costs data regarding cultivation, transport and the capital and operational costs of biomass processing are exogenously determined and supplied to the BioScope optimization model. The key outputs of the model are the locations and the scales of the industrial processing facilities and the amount of biomass transported from each biomass region to existing and new industrial processing locations. These results are used to calculate the total ethanol production costs per biomass supply region. The optimised total ethanol production costs of sugarcane processing are 894 $US\$_{2014}/m^3$ ethanol in 2015 and decrease to 752, 715 and 710 $US\$_{2014}/m^3$ ethanol in 2030 for the multi-step, one-step and greenfield expansion respectively. For eucalyptus, the ethanol production costs decrease from 635 $US\$_{2014}/m^3$ in 2015 to 560, and 543 $US\$_{2014}/m^3$ in 2030 for the multi-step and one-step (greenfield) approach respectively. These costs differ only marginally for the different optimization approaches used for the 2030 projections due to the utilization of the same biomass supply regions and the small variation in capital investment costs of industrial plants. By optimizing the ethanol production costs for the state of Goiás as a whole, the size and location of individual industrial processing plants may be suboptimal for a smaller region, but they are part of the optimal solution for the whole state of Goiás.

Chapter 6 employed a discounted cash flow spreadsheet to calculate the biobased production costs of the different industrial processing pathways producing ethanol, ethylene, 1,3 propanediol and succinic acid. The cash flow include the expenses for sugarcane or eucalyptus feedstock, investment, maintenance, operational expenses, labour, and energy inputs. To enable a comparison among the different biobased production pathways and their fossil reference, a uniform approach and assumptions are applied. For such comparison, the production costs and GHG emission intensity are xpressed in US$/kg final product and kg CO_{2eq}/kg final product respectively. In addition, the GHG emissions reduction (with respect to their fossil equivalent product) and potential total profit per hectare of feedstock cultivation is applied. These functional units enable a comparison between the utilization of sugarcane or eucalyptus as biomass feedstock.

The range of biobased product production costs with a 60% confidence interval are 0.64 – 1.10 US$/kg ethanol, 1.18 – 2.05 US$/kg ethylene, 1.37 – 2.40 US$/kg 1,3 PDO and 1.91 – 2.57 US$/kg succinic acid. All biobased products partly or completely overlap with the range of production costs of the fossil equivalent products. The results shows that sugarcane based 1,3 PDO and to a lesser extent the production of succinic acid have the highest economic potential for large-scale industrial processing. At an oil price of 50 $/barrel, the ethanol and ethylene production pathway have difficulty to directly compete with the fossil products price, while the production of 1,3 PDO and succinic acid production from sugarcane and the production of eucalyptus based succinic acid are profitable. The economic assessment in this study does not consider the possible impact of taxes, tax exemptions, or premiums payed for biobased products. The variation in petrochemical products is based on a variation in the crude oil price between 40 and 130 US$/bbl. With current oil prices of 50 US$/bbl, most of the biobased production pathways have difficulty to compete, but increasing oil prices can increase the economic viability.

The assessments of the economic performance of region specific biobased supply chains show that generally feedstock costs have a large to the total ethanol production costs. For the production costs of first generation ethanol production, the biomass feedstock are the largest contribution to total ethanol production costs. For second generation ethanol production, feedstock costs are important, but capital depreciation and costs for enzymes plays also a prominent role. For biobased chemicals the capital depreciation and energy become even more prominent. This originates mainly from the capital investment and energy consumption related to the product recovery and purification of biobased chemicals after fermentation.

What are the trade-offs between the GHG balance and economic performance of different biobased supply chains for different regions?

For the case of pine plantations in the US, chapter 2 clearly illustrates that carbon debt payback times can be drastically reduced by increasing yields through intensive management. However, at current market prices for wood products, such strategies are not currently viable. The trade-offs between the economic performance and GHG emission intensity are also illustrated in chapter 3, as this chapter simultaneous quantifies the costs and overall carbon balance of different pine plantation management strategies. Switching from the current conventional plantation management strategy without the use of slash for bioenergy to an additional thinning strategy with the use of slash increases the overall carbon accumulation by about 31%, at marginally higher wood supply cost. Compared to the other strategies, the additional thinning strategy has the highest total wood yield, of which a large portion is classified as chip-n-saw and sawtimber. The yield of higher-value wood classes for the additional thinning strategy also returns low pulpwood cultivation costs and additional slash (if applicable), making this strategy the most economically attractive for landowners. However, forest owners need to decide on planting strategies decades before they may (possibly) reap the benefits of a changed management strategy. Given the uncertain reward that forest owners may (or may not) receive for additional carbon sequestration, it is questionable if landowners will actually accept the risks involved with this trade-off.

One possibility to illustrate the trade-off of additional costs and the additional carbon accumulation of the different plantation management strategies is to express them as CO_2 abatement costs. Carbon dioxide abatement costs are calculated for the plantation management strategies using the difference in both the total carbon balance and the plantation management costs compared to the conventional strategy. As shown in Table 3-9 of chapter 3, the CO_2 abatement costs vary between -13 and 21 US$/Mg CO_2.

Illustrating that in some cases, win-win situations may occur, whereas in other cases, additional carbon sequestration comes at a cost.

Other trade-offs occur in the economic performance or within the GHG balance:

- Biomass yield increase seems an evident option to reduce costs (and typically also GHG emissions), but yield increase in terms of dry matter should not be at the expense of favourable characteristics, such as the sugar content of sugarcane, or the glucan content of lignocellulosic feedstock, if the feedstock is converted through a biochemical conversion route. Furthermore, also transportation costs can be reduced when biomass yield is increased, but this only has a marginal impact on total production costs. (Chapter 4).
- Chapter 5 shows that large scale industrial processing is preferred due to clustered biomass supply, low transportation costs and economies of scale for industrial processing. In several cases, the maximum allowable scale (as set in the optimization model) of industrial plants was reached. Optimal locations differ among the different expansion approaches used. In most cases industrial plants are preferred in high yielding biomass supply regions to reduce average transportation costs.
- Chapter 6 considers the GHG emission intensity and potential profit of 4 products using different metrics. A key result is that the industrial processing pathways utilizing sugarcane showt in higher GHG emission reduction and potential net profit compare to eucalyptus utilization. Sugarcane to 1,3 PDO production has the highest profit margin (3211 US$/ha-year) and GHG emission reduction per kg biobased product (5.2 kg CO_2/kg). However, succinic acid production has a higher GHG emission reduction potential per hectare; 41 Mg/ha-year for succinic acid compared to 33 Mg/ha-year for 1,3 PDO. Yet, in relative terms compared to their fossil fuel counterparts, biobased ethanol and ethylene achieve the highest GHG emission reduction, but their economic performance is less competitive. These examples illustrate that determining ‘optimal’ biobased production pathways is far from trivial, and depends on the chosen optimisation objective (economic profitability, GHG emission reduction or both), and the chosen metric to measure economic and GHG performance.

7.4 Key messages and recommendations

Key messages

Carbon debt payback times and offset parity points can be actively and shortened by choosing smart management strategies and maximizing carbon displacement effects of harvested wood. The carbon debt payback period and carbon offset parity periods are influenced by biomass yield, carbon replacement factor, system boundaries and the choice of reference scenario. This dissertation shows that switching to highly productive plantations increases the uptake of carbon strongly, which offsets the additional emissions of silvicultural practices by far. However, based on the results found in Chapter 3, it can be concluded that the total wood volume yield is not per se the best criterion for the selection of the best plantation management strategies to accumulate carbon. The plantation management strategy which yields high volumes of sawtimber and chip-n-saw avoids more GHG emissions, especially for the longer timeframe. To achieve high carbon displacement the interplay between the harvested wood yield and the associated carbon displacement of the harvested wood is important.

Ethanol production costs in Brazil can be reduced considerably in the future. The ethanol production costs of first generation industrial processing can decrease by reduced feedstock costs, increased sugar content, and upscaling of industrial facilities. The use of optimized technology, collection and use of sugarcane trash, and the use of sweet sorghum reduce ethanol production costs even further. For second generation industrial processing the reduced feedstock costs, increase in industrial efficiency, upscaling, and the use of optimized technology are factors to reduce ethanol production costs. Overall, total cost reduction found in this study are 48%, 41%, and 53% for first generation, integrated first-and-second generation and second generation industrial processing. Overall, the production second generation ethanol using eucalyptus can result in the lowest ethanol production costs in 2030.

Direct land use change GHG emissions can affect the GHG emission intensity of ethanol production both positively and negatively. When cropland is converted to sugar cane, carbon can be sequestered in both soil and biomass carbon. This contributes to a high GHG emission reduction potential of sugar cane ethanol. However, the GHG emission mitigation potential of ethanol can be completely vanished when high carbon stock land is converted. Therefore, the location of land use changes for biomass cultivation highly affects the GHG performance of biomass supply chains.

Biobased chemical production can be profitable and can achieve significant GHG emission reduction – but picking winners is complex. The reported cost ranges of the biobased products partly overlap with the ranges of their fossil reference products. Sugarcane based 1,3 PDO and the production of succinic acid have the highest economic viability,. However, the costs of these production pathways are more uncertain compared to the more established ethanol and ethylene production. The GHG emission reduction per kg biobased product differs considerably: GHG savings between 3 and 105% are found. Overall, it was not possible to choose a clear winner, as a) the best-performing product strongly depends on the chosen metric, and b) the ranges found in the production costs and GHG emissions are very large, , especially for PDO and succinic acid, independent of the chosen metric.

Recommendations to industry and policymakers

- To quantify the carbon payback period and carbon offset parity periods the selection of methodological perspective and reference scenario are key factors. Furthermore, the forest growth rate and carbon displacement are important elements. With this in mind, carbon payback times can be actively and significantly reduced with active management strategies aiming at both maximizing yield and producing wood products with high carbon displacement effects. Some of these strategies (e.g. increasing the initial planting density) may already be economically viable; others (increasing overall yields) will require additional policy support. However, a change of plantation management, to sequester more carbon, would require an upfront investment. Therefore, support for plantation owners should be consistent and take into account the plantation cycle time.

- For biomass crops the increase in biomass yield seems an evident option to reduce costs, but yield increase in terms of dry matter should not be at the expense of favourable characteristics, such as the sugar content of sugarcane, or the glucan content of lignocellulosic feedstock. The sugar content of sugarcane is one of the main improvement options of first generation ethanol production. Therefore, crop improvement should be considered together with the (expected) demand for biomass crop characteristics.
- Many of the analyses performed in this study consider the n^{th} plant technology. However, the development of novel industrial processing technologies, like second generation and biobased chemical production, require considerably investments in research and development and upscaling before large-scale production facilities can be utilized. Therefore, a radical shift to novel industrial processing options seems less likely.
- The selection of the optimal utilization of biomass is not straightforward as its performance can be expressed in different metrics, each with a different ranking of biomass supply chain configurations. Therefore, a clear guidelines for the preferred metric can support the comparison and selection of best performing biomass use option(s).

Directions for further research

The economic and GHG performance of different biomass supply chains is quantified for wood pellet production in the Southeastern USA and ethanol production in Brazil. The ex-ante analyses demonstrated in this dissertation provide better founded insights in the potential development and implementation strategies for biomass use in the future. Future analyses of the total GHG balance of biomass supply chains require more detailed quantification of the following elements:

- The importance of carbon stock change; either the initial carbon stock change of forestry biomass or the carbon stock change due to land-use change for biomass crop production. This includes a detailed assessment of where this direct, and potentially also, the indirect land-use change would occur.
- For forestry biomass, more information is required about the impact of management practices, including slash collection and use for bioenergy, on the different carbon pools is required. Especially, the relation between increased wood extraction and soil organic carbon is not well understood.
- More detailed information on the forest growth rates, especially the diameter growth rate, and carbon displacement factors will improve the robustness of the results of the economic analysis and especially the carbon balance of forestry biomass.

- The use of fertilizers plays an important role in the GHG emissions of sugarcane, eucalyptus and softwood cultivation. More knowledge on the application rate of fertilizers, relationship between biomass yield and fertilizer application rate, and the optimization of fertilizer use could help to reduce the impact of fertilizers on the overall GHG balance of biomass supply chains.
- Softwood is nowadays mainly used to produce wood pellets for the heat and electricity market. Carbon payback times of potential advanced other products produced from softwood (e.g. 2nd generation biofuels and durable bioplastics) should also be investigated to identify optimal GHG mitigation strategies.
- For second generation ethanol production and the production of biobased chemicals, the use of process energy is sometimes uncertain. Better data regarding the use of process energy would improve the determination the GHG emission balance of these products.

To improve the insights in the economic performance, or the robustness of the results, future research should focus on:

- Biomass yield is responsive to soil quality, climate conditions and plantation management intensity. A better quantification of the biomass yield in relation to these site and case specific characteristics can reduce the uncertainty of biomass yield level, and so, improve the robustness of economic analysis. Furthermore, the use of plantation management-, harvest-, or processing residues are important for the economic performance. More insight is required in the costs associated with the mobilization and use of these residues as feedstock for biomass supply chains.
- More detailed quantification of the conversion efficiencies of advanced biorefineries, based on insights from pilot or demonstration units of biobased chemicals will reduce the uncertainties in the prospective economic analysis of industrial size processing facilities.
- A more detailed analysis of equipment costs, scaling factors, maximum scale and total investment cost of the different industrial processing steps would improve the robustness of the total investment costs of advanced biorefineries.
- More insight in the inputs and especially the energy consumption of new industrial processes for the fermentation and recovery of novel biobased products, including industrial pathways with multiple main products and more complex biorefinery concepts.

The different chapters of this dissertation demonstrate the importance or impact of embedding biomass supply chains in the already existing land-use and biomass use sectors. While in this thesis, the focus was mainly on biorefineries with one or two main products, further research should focus on the integration of different biomass use options, multi-input industrial processes, or co-production of different products are potential options for the future. Integration strategies may reduce costs or GHG emissions, but also lead to co-benefits with respect to the efficient use of agricultural land or forest plantations. A key element to include in such analyses is the possible impact on market prices of biochemicals at the moment biobased chemicals reach a high market penetration rate. Also, the combined and ex-ante use of the methods demonstrated in the thesis in emerging biomass regions can give better founded insights in optimal roadmaps and implementation strategies for biobased economy options over time.

Finally, this dissertation solely focussed on the economic and GHG performances of different biomass supply chains. Other aspects, such as overall environmental impacts (e.g. on biodiversity, requirements to meet sustainable forest management criteria) and socio-economic impacts (e.g. possibly additional job creation) need to be further investigated. Therefore, more research as well as policy focus is desired on how biomass production systems and value chains can be optimally combined with better land use strategies, including more efficient and sustainable agricultural and forestry practices. Such strategies can not only optimize biomass production and deployment, but may also lead to co-benefits with respect to more resource (land, water, nutrients) efficient agriculture and resilient forests.

Chapter 8

Samenvatting, conclusies and aanbevelingen

8.1 Achtergrond en context van het onderzoek

Er is een wijdverbreide wetenschappelijke consensus dat de wereldwijde klimaatverandering met een hoge mate van zekerheid wordt veroorzaakt door de verhoogde concentratie van antropogene broeikasgassen (BKG) in de atmosfeer (IPCC, 2014b). De aanhoudende uitstoot van broeikasgassen leidt uiteindelijk tot ernstige en onomkeerbare gevolgen voor mensen en ecosystemen. Daarom is een substantiële en aanhoudende reductie van antropogene broeikasgasemissies noodzakelijk om de impact van klimaatverandering te beperken (IPCC, 2014b). De teelt en inzet van biomassa voor de productie van elektriciteit, biobrandstoffen en chemicaliën wordt gezien als een belangrijke optie om BKG emissies te reduceren (Chum et al., 2011, IPCC, 2014b). Een toenemende vraag naar biomassa zal inherent een toename van het aanbod betekenen. Er bestaat echter onzekerheid over het aanbod van biomassa in de toekomst. De schattingen van het aanbod van biomassa voor 2050 verschillen met een factor 3 in omvang (IPCC, 2014a). De literatuurstudie van Creutzig et al (2015) kwalificeerde het duurzame biomassa potentieel op basis van de overeenstemming tussen wetenschappers; tot en met 100 EJ_{PRIM}/jaar in 2050 bereikte een hoge mate van overeenstemming, terwijl een aanbod van 100-300 EJ_{PRIM}/jaar gekwalificeerd werd met medium overeenstemming (Creutzig et al., 2015). Aangezien de beschikbare biomassa niet ongelimiteerd is, is het van belang het potentieel van biomassa om broeikasgassen te reduceren effectief te benutten.

Het gebruik van biomassa zal niet per definitie leiden tot een BKG-emissiereductie ten opzichte van de fossiele referentie. Het BKG-emissiereductiepotentieel is onlangs ter discussie gesteld met het meenemen van de verandering in koolstofvoorraad in de totale BKG-balans (Cherubini, Guest, & Stromman, 2013; Searchinger, 2009). Om de BKG-balans van biomassa ketens te kwantificeren en te vergelijken, moeten deze de BKG-emissies van de keten als ook de BKG emissies door landsgebruik verandering bevatten. De BKG balans wordt beïnvloed door de BKG-boekhoudmethode, evenals de selectie van het biomassa gewas, het plantage beheer, de biomassa-opbrengst en de selectie van de conversietechnologie. Deze kenmerken zijn regio- en casus-specifiek en veranderen in de tijd. Daarom moet de BKG-balans van huidige en toekomstige biomassa-ketens worden gekwantificeerd met een uniforme aanpak waarbij rekening wordt gehouden met regio- en casus-specifieke parameters en gegevens.

De economische haalbaarheid van biomassa ketens is een belangrijke voorwaarde voor grootschalig toepassing. De productie van bioenergie, biobrandstoffen en biochemicaliën zal economisch moeten kunnen concurreren met fossiele equivalenten. Om een transparante vergelijking tussen de economische prestaties van verschillende biomassa ketens mogelijk te maken, is het gebruik van een uniforme aanpak, met vergelijkbare economische aannames, schaal, etc. vereist. Om de kosten voor de inzet van biomassa en voor de daarmee vermeden fossiele bronnen te bepalen, moet een vergelijkbare analyse-eenheid worden gekozen. Echter, uniforme, geharmoniseerde economische evaluaties van verschillende biomassa-ketens die een goede vergelijking mogelijk maken zijn niet in de literatuur gevonden.

Op basis van de hiaten in de bestaande literatuur zijn belangrijke onderwerpen voor onderzoek: 1) De methoden die worden gebruikt voor de kwantificering van de economische prestatie en het emissiereductiepotentieel van het gebruik van biomassa, 2) Regiospecifieke casestudies voor de economische prestaties en de BKG emissies van grootschalige productie van elektriciteit, brandstoffen en chemicaliën. Bovendien kan een gedetailleerde kwantificering van de economische prestaties en de BKG-balans ook de mogelijke trade-offs tussen deze belangrijke indicatoren tonen.

Twee zeer belangrijke biomassa productie ketens van dit moment zijn de productie van houtpellets in het Zuidoosten van de VS, voornamelijk voor de elektriciteitsproductie in Europa en de suikerriet-ethanolproductie in Brazilië. Deze regio's zijn belangrijke biomassa producenten en leveren een belangrijke bijdrage aan de wereldwijde bio-energievoorziening. Beide productiegebieden kunnen hun productie in de komende decennia aanzienlijk uitbreiden door de uitbreiding van het areaal, verbeteringen in de agrarische- en industriële opbrengst en door de invoering van nieuwe industriële processen en waardeketens.

8.2 Onderzoeksvragen en raamwerk van het proefschrift

Het doel van dit proefschrift is het evalueren, combineren en harmoniseren van verschillende methoden om de broeikasgasemissies en de economische prestaties van regio-specifieke biomassa-ketens uniform te kwantificeren en te vergelijken. Daartoe worden de volgende onderzoeksvragen behandeld:

1. Hoe kan de totale BKG-balans van biomassa ketens voor de productie van elektriciteit, brandstoffen en chemicaliën uniform worden gekwantificeerd en wat is de BKG-balans voor specifieke regionale casestudies?
2. Hoe kan de economische prestatie van biomassa ketens voor de productie van elektriciteit, brandstoffen en chemicaliën uniform worden gekwantificeerd en wat is de economische prestatie van specifieke regionale casestudies?
3. Wat zijn de trade-offs tussen de BKG-balans en de economische prestaties van verschillende biomassa ketens voor verschillende regio's?

Bij het beantwoorden van deze vragen worden verschillende biomassa-ketens voor de productie van elektriciteit, brandstoffen en chemicaliën geëvalueerd. Deze ketens hebben betrekking op verschillende biomassa-gewassen, plantagemanagementstrategieën, oogsttechnieken industriële processen en eindproducten. Zie tabel 8-1 voor een overzicht van de verschillende hoofdstukken en de geadresseerde onderzoeksvragen. Dit wordt gevolgd door de antwoorden op de drie hoofdonderzoeksvragen van dit proefschrift.

Tabel 8-1.

	Hoofdstukken en hoofdstuktitels	Onderzoeksvragen 1	2	3
2	Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States	x		
3	Carbon balances and economic performance of pine plantations for bioenergy production in the Southeastern United States	x	x	x
4	Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies		x	
5	Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil	x	x	x
6	Economic performance and GHG emission intensity of sugarcane and eucalyptus derived biofuels and biobased chemicals in Brazil.	x	x	x

8.3 Antwoorden op de onderzoeksvragen.

Hoe kan de totale BKG-balans van biomassa ketens voor de productie van elektriciteit, brandstoffen en chemicaliën uniform worden gekwantificeerd en wat is de BKG balans voor specifieke regionale casestudies?

In dit proefschrift worden drie belangrijke aspecten van de BKG-balans van biomassaketens in detail besproken: de eerste is de uitstoot van broeikasgassen tijdens de teelt, transport en verwerking naar biobased eindproducten. Het tweede aspect is de verandering van de koolstofvoorraad als gevolg van de extractie van biomassa uit bossen. Het derde aspect is de BKG emissies in verband met de verandering van het landgebruik voor biomassa-teelt. De bevindingen van dit proefschrift met betrekking tot deze drie aspecten en hun prestaties worden hieronder in detail besproken.

BKG-uitstoot in de keten

De broeikasgasemissies van teelt, transport en industriële verwerking worden gekwantificeerd voor naaldhoutbiomassa in Zuidoost-Amerika (hoofdstukken 2 en 3), ethanolproductie in de staat Goiás (hoofdstuk 5) en verschillende biobased producten, waaronder ethanol (hoofdstuk 6).

In hoofdstukken 2 en 3 worden de broeikasgasemissies van de teelt, oogst, transport, verwerkings- en eindproductgebruik gekwantificeerd als onderdeel van de totale koolstofbalans. In deze koolstofbalans wordt rekening gehouden met de broeikasgasemissies van plantagebeheer, oogst en transport, koolstof in levende en dode bomen, vastgelegd koolstof in houtproducten en vermeden uitstoot van koolstof als gevolg van productvervanging. De broeikasgasemissies van het plantagebeheer worden bepaald op basis van het gebruik van kunstmeststoffen, het verbruik van agrochemicaliën en het dieselgebruik van verschillende bosbouwpraktijken. Voor hoofdstuk 2 wordt de uitstoot van broeikasgassen beschouwd voor het oogsten van hele bomen en uitgedrukt per ton geleverde houtpellets. De totale broeikasgasemissies liggen tussen 355 en 420 kg CO_2 per ton pellets. De uitstoot van BKG gerelateerd aan plantagebeheer voor de lage, middelgrote en hoge opbrengst strategieën veroorzaakt het verschil. Voor hoofdstuk 3 worden de totale broeikasgasemissies economisch gealloceerd aan de verschillende geoogste houtklassen. Het samenvoegen en alloceren van de broeikasgasemissies van oogsten, verzamelen en transporteren met de broeikasgasemissies van de teelt resulteert in de totale uitstoot van broeikasgassen voor pulphout en houtresiduen. De uitstoot van broeikasgassen voor het beheer (met uitzondering van oogsten) van naaldhoutplantages in de zuidoostelijke Verenigde Staten is tussen 3,7 en 7,2 kg CO_2/Mg droog pulphout. Samen met oogsten en transport bedragen de totale broeikasgasemissies voor het leveren van hout aan industriële verwerkingsfaciliteiten 27 tot 33 kg CO_2/Mg droog pulphout. Om rekening te houden met de broeikasgasemissies en de reductie in uitstoot van broeikasgasemissies in de rest van de toeleveringsketen en de gebruiksfase, wordt het geoogst hout gecategoriseerd in vier verschillende houtproductcategorieën (lang, middel lang, medium kort en korte omloop houtproducten), elk met een specifieke substitutiefactor. De koolstofsubstitutiefactor in een indicatie van de koolstofefficiëntie van het gebruik van houtproducten in vergelijking met het gebruik van andere materialen en kwantificeert de hoeveelheid vermeden BKG-uitstoot, in lijn met de definitie van (Sathre & Connor, 2010). Met andere woorden; deze geaggregeerde factor geeft de uitstoot van broeikasgassen door houtgebruik aan in vergelijking met het gebruik van alternatieve producten. De substitutiefactor voor de verschillende houtklassen zijn 2,1, 1,8, 1,5 en 0,5 voor de houtklassen zaaghout, chip-en-zaag, pulphout en residu-hout respectievelijk.

In hoofdstuk 6 wordt de totale BKG emissie intensiteit van verschillende biobased producten bepaald. De broeikasgasemissies van biomassa-teelt en -transport zijn bepaald door gebruik te maken van gegevens die reeds zijn gepubliceerd in andere studies voor suikerriet- en eucalyptus. Een massa- en energiebalans is opgesteld om de biobased productopbrengst en de broeikasgasemissies te bepalen, uitgedrukt in kg CO_2 per kg biobased product bij het verlaten van de fabriek. De uitstoot van broeikasgassen omvat de toevoer van grondstoffen, industriële verwerkingsemissies en de uitstoot van broeikasgassen die verband houden met het additionele stoom-, warmte- en elektriciteitsgebruik. De totale BKG-emissie intensiteit van ethanolproductie met suikerriet- en eucalyptus als biomassa gewas ligt in tussen de -0,08 en 0,72 kg CO_2/kg ethanol. Ook de ethyleenproductie, mede door de vermeden BKG-emissies, resulteert in een lage BKG-emissie intensiteit (0,25 - 0,68 kg CO_2/kg ethyleen) in vergelijking met de petrochemische referentie. Biobased 1,3 PDO en barnsteenzuur hebben een GHG emissie intensiteit vergelijkbaar met de fossiele referentie, respectievelijk 1,80 - 3,68 kg CO_2/kg PDO en 2,24-4,55 kg CO_2/kg barnsteenzuur.

De BKG-emissies in de keten die in dit proefschrift worden gekwantificeerd, worden uitgedrukt in verschillende eenheden. Deze keuze verschilt dus per hoofdstuk; daarbij is gekeken welke het meest geschikt is voor de vergelijking van de individuele casestudies.

Bosbouw koolstof boekhouding

De verandering van de koolstofvoorraden van biomassa uit de bosbouw wordt geanalyseerd door gebruik te maken van de dynamische koolstofbalansbenadering; een overzicht van alle koolstofvoorraden en hun verandering over de tijd. Deze koolstofbalans is de som van de in-situ (koolstof in levende bomen, koolstof in dode bomen en koolstof in residuen na oogsten) en ex-situ (biogene koolstof opgeslagen in geoogste houtproducten en vermeden fossiele koolstof als gevolg van productvervanging) koolstofvoorraden (Hoofdstuk 3). In hoofdstuk 2 wordt het GORCAM carbon boekhoud model gebruikt om koolstofvoorraden en voorraadwijzigingen van koolstof in naaldhoutplantages in de zuidoostelijke Verenigde Staten te bepalen. Terwijl hoofdstuk 3 inzoomt op de impact van plantagebeheerstrategieën en bepaalt de impact van de beheersstrategieën op individueel boomvolume en aantal levende bomen om het totale houtvolume per hectare per jaar van de rotatieperiode te bepalen. De volumegroeicurve van loblolly-pinebomen en de geoogste houtklassen zijn de belangrijkste input voor het alloceren van de BKG-uitstoot van plantagebeheer en om de in-situ en ex-situ carbon voorraden te berekenen (Hoofdstuk 3).

Zoals besproken in hoofdstuk 2, zijn belangrijke aspecten die invloed hebben op de koolstofbalans opbrengsten, koolstofvervangingsfactoren, systeemgrenzen en de keuze van het referentiescenario dat gebruikt wordt om het pariteitspunt te bepalen. Elk van deze vier aspecten wordt hieronder uitgebreider besproken:

Hoofdstuk 2 wijst erop dat het overstappen naar zeer productieve plantages de koolstofopname sterk verhoogt, waardoor de extra uitstoot van plantage beheer grotendeels gecompenseerd wordt. Verhoogde uitstoot voor plantagebeheer wordt gecompenseerd door snellere (her-)groei van plantages, waardoor de opname van koolstof en het vermijden van fossiele brandstof na de oogst verhoogd wordt. Het vergelijken van de broeikasgasemissies in de keten met de vermeden fossiele brandstoffen heeft de lage opbrengst plantage (30 Mg koolstof/ha na 75 jaar) uitgestoten, terwijl de cumulatieve vermeden broeikasgasemissies 188 Mg koolstof/ha zijn. Voor de hoge productieve strategie zijn deze waarden respectievelijk 73 Mg koolstof/ha voor de keten en 339 Mg koolstof/ha vermeden BKG emissies. In hoofdstuk 3 wordt de impact van plantagebeheerstrategieën op boomgroei en groeisnelheid geanalyseerd. De hoofdvariabele in de boomgroei-simulatie is de diametergroei, aangezien het de belangrijkste parameter voor zowel boomvolume als productclassificatie is. Hoewel de diametergroei parametrisering gebaseerd is op een oudere studie (Pienaar, Shiver, & Harrison, nd), vertoonde de recentere analyse van (Zhao, Kane, & Borders, 2011) een soortgelijke diameter groeicurve zoals gesimuleerd in de huidige analyse. Echter, de parametrisering van de groeivergelijkingen die voor deze studie werden gebruikt, zijn gebaseerd op empirische gegevens voor lagere plantdichtheden. Om hogere plantdichtheden te modelleren, zouden meer empirische gegevens voor een betere parametrisering wenselijk zijn. Op basis van hoofdstuk 3 kan geconcludeerd worden dat de totale opbrengst van het houtvolume niet per se het beste criterium is voor de selectie van plantagebeheerstrategieën om koolstof vast te leggen. Bijvoorbeeld, de houtopbrengst van de KortRotatie-beheer strategie is hoog, maar levert hoofdzakelijk pulphout op, dat een lagere substitutiefactor heeft (tabel 3-6, hoofdstuk 3). Gezien het verschil tussen de Conventionele en de Extra-uitdunningstrategie; De extra uitdunningstrategie produceert meer hout, terwijl de hoeveelheid zaag- en chip-n-zaaghout in beide strategieën gelijk is. Zo resulteert de toevoeging van pulphoutoogst in een hogere verplaatsing van fossiele koolstof, aangezien het de houtopbrengst van andere houtklassen niet beïnvloedt. De hoge pulphoutopbrengst in de strategie voor korte rotatiestrategie compenseert niet voor de verlaagde koolstofsubstitutiefactoren voor pulphout in vergelijking met zaaghout.

Vooral voor simulatietijden van 100 jaar en langer wordt de koolstofbalans gedicteerd door de vermeden koolstof door product substitutie, in tegenstelling tot de stabiliserende biogene koolstof die in houtproducten is vastgelegd. De studie van (Perez-Garcia, Lippke, Comnick & Manriquez, 2006) illustreerde ook het hoge aandeel van verplaatste koolstof in het totale koolstofbalans, vooral over langere perioden. Aangezien houtpellets direct kolen vervangen in hoofdstuk 2, lijkt een substitutiefactor van 0.92 (ton koolstof vermeden per ton koolstof geoogst) gerechtvaardigd. Het probleem met deze generieke koolstofsubstitutiefactoren is het gebrek aan gegevens over houtverwerking, gebruik en levensduur van houtproducten, en de afvalverwerking van houtproducten (Brunet-Navarro, Jochheim, & Muys, 2016). Door de koolstofsubstitutiefactoren wordt de invloed van de verschillende opbrengsten van verschillende houtklassen inzichtelijk op de koolstofbalans buiten de bosplantage. Daarom geeft deze analyse een beter beeld van de impact van de beslissingen van de plantagebeheer op het totale koolstofbalans. Tenslotte is het discutabel of de koolstofsubstitutiefactoren voor de komende 100 jaar constant moeten worden gehouden. Door de ontwikkeling van producten en technologieën kan de uitstoot van broeikasgassen van houtproducten of van de alternatieve producten namelijk veranderen.

De keuze van de methodologische benadering heeft een grote impact op de berekening van de koolstofterugverdientijd en de koolstofpariteitsperiode (hoofdstuk 2). Uit hoofdstuk 2 ten aanzien van de koolstofbalans blijkt duidelijk dat de keuze van de koolstofboekhoudkundige methode een significante impact heeft op de koolstofterugverdientijd en koolstofpariteitsperiode. In hoofdstuk 2 wordt een enkel-perceels-benadering (statische systeemgrens), toenemende perceel-benadering (dynamische systeemgrens) en een landschapsbenadering (statische systeemgrens) gebruikt. Zoals ook aangegeven door (Sintas 2017), hangt de keuze voor de methodologische aanpak sterk af van het doel ervan. We beschouwen de aanpak van de koolstofschuld op landschapsgebied beter geschikt voor de situatie in de zuidoostelijke Verenigde Staten, waar naaldhoutplantages veel voorkomend zijn. Voor de in hoofdstuk 3 omschreven doelstellingen; kwantificering van de impact van plantagebeheerstrategieën op de koolstofbalans, is het gebruik van de perceels benadering gerechtvaardigd.

Ten slotte wijst hoofdstuk 2 erop dat in onze casus de keuze van 'geen-oogst' als referentie scenario voor de koolstofpariteitsperiode berekeningen niet eenduidig is. Door de interviews met bosbouw deskundigen in Zuidoost-Verenigde Staten beschouwen we de 'niet-oogst'- en 'natuurlijke hergroei'-scenario's als niet realistisch; zonder financiële compensatie is het waarschijnlijk dat plantages die niet worden geoogst voor hout / vezel, omgezet worden in bijvoorbeeld stedelijke ontwikkeling of landbouwgrond. In een dergelijk geval zou geen of aanzienlijk minder koolstof in het referentiescenario worden vastgelegd, wat dan waarschijnlijk veel slechter zou zijn dan elk bio-energie scenario.

Uit de resultaten van hoofdstuk 2 blijkt dat de koolstofterugverdientijd van een perceel, met behulp van de enkel-perceel benadering, varieert van 5 tot 11 jaar, afhankelijk van de bosbeheers-intensiteit. Voor het koolstofpariteitsperiode, met behulp van de toenemende perceelsbenadering, hebben de oogstscenario's de voorkeur na 17-39 jaar. Voor de landschapsbenadering liggen de resultaten verder uit elkaar: van een 46-jaar CO_2-pariteitstijd in het ergste geval tot slechts 12 jaar voor een scenario met hoge-beheersintensiteit. Wanneer alleen de koolstofschuld op landschapsniveau wordt bekeken, worden de tijdstippen om het evenwichtspunt te bereiken verwaarloosbaar, d.w.z. korter dan 1 jaar. De meeste andere studies (Walker et al., 2010; Zanchi et al., 2010; Colnes et al., 2012; Mitchell et al., 2012) gebruiken de koolstof pariteitsperiodemethode. Wanneer we onze resultaten met deze studies vergelijken, vinden we dat het koolstofpariteit na 17, 22 en 39 jaar bereikt wordt voor de toenemende perceel benadering. Bij toepassing van de landschapsbenadering wordt na 12, 27 en 46 jaar het koolstof pariteitspunt bereikt voor het hoog-, medium- en laagproductief scenario. Deze tijden zijn korter dan de tijdstippen die zijn geïdentificeerd door de hierboven genoemde studies, die koolstof terugverdientijden van <1 jaar voor houtpelletproductie op voormalige landbouwgrond vinden (Zanchi et al., 2010; Mitchell et al., 2012), tussen 16 En 90 jaar op voormalig beboste grond (Walker et al., 2010; McKechnie et al., 2011) en 19 tot 1000 jaar voor oude bossen (Zanchi et al., 2010; Mitchell et al., 2012).

Bij het inzoomen op de impact van plantagebeheerstrategieën op de koolstofbalans, zoals in hoofdstuk 3 wordt weergegeven, is de totale koolstofvoorraad na 100 jaar 205 (247), 214 (268) en 149 (195) Mg koolstof/ha voor de Conventionele, Extra uitdunning en Korte Rotatie management strategieën (in de haakjes zijn dezelfde strategieën met residu). Voor de gemiddelde lineaire koolstof-trendlijn is de koolstofvoorraad echter respectievelijk 213 (244), 216 (259) en 194 (242) Mg koolstof/ha voor de Conventionele, Extra uitdunning en Korte Rotatie loblolly pine plantage management strategieën. Door de classificatie van geoogst hout naar de verschillende houtklassen, elk met een specifieke koolstofsubstitutiefactor, wordt de geaccumuleerde vermeden koolstof in grote mate bepaald door de opbrengst van zaag- en chip-n-zaag klasse hout. Het is belangrijk om op te merken dat de resultaten specifiek zijn voor naaldbossen in de zuidoostelijke VS, en kunnen variëren naargelang de regionale verschillen.

BKG-uitstoot in verband met landgebruiksverandering

Belangrijke aspecten om landgebruik broeikasgasemissies te kwantificeren, zijn de verdeling van biomassa-aanbodregio's; hun vroegere en huidige koolstofvoorraden, biomassa-opbrengst en industriële conversiemogelijkheden na de oogstteelt.

De verwachte distributie van biomassa-aanbodgebieden is een belangrijk element in de optimalisatie van de gehele biomassa-keten. Dit is gedaan voor de staat Goiás in Brazilië, zoals getoond in hoofdstuk 5, waarbij de ruimtelijk expliciete biomassa productiegebieden worden bepaald door het landgebruiksverandering model PLUC. Door gebruik te maken van PLUC kunnen de vooraf gedefinieerde biomassa-aanbodregio's, potentiële locaties van nieuwe industriële verwerkingsinstallaties, de transportafstand tussen productiegebieden en verwerkingsinstallaties en de BKG uitstoot van landgebruiksveranderingen worden gekwantificeerd. Het is belangrijk om op te merken dat de economische doelstelling van de optimalisatie bepalend is voor de keuze van het aantal en de locatie van de industriële faciliteiten (verlaging van de transportkosten) en het beperken van de kapitaalkosten van industriële installaties. Daarom toont deze analyse alleen de potentiële BKG emissie-intensiteit bij gebruik van een economisch optimaliseringsdoel met al bestaande biomassa-leveringsgebieden. Een optimalisatie van de BKG-emissie intensiteit van ethanolproductie in Goiás is niet uitgevoerd in hoofdstuk 5.

De agro-ecologische geschiktheid (ruimtelijk heterogeen) en de maximale opbrengstwaarde (tijdvariabele) bepalen gezamenlijk de biomassa-opbrengst in de biomassa aanbodgebieden. De combinatie van de distributie van biomassa-aanbodgebieden en de wisselende opbrengsten van de leveringsgebieden is een belangrijk kenmerk van deze studie en resulteert in de ruimtelijke heterogene beschikbaarheid van biomassa.

De BKG-emissie intensiteit van ethanolproductie met behulp van de economisch optimale ketens wordt gedomineerd door de BKG emissies van directe landgebruiksveranderingen. Het is belangrijk om op te merken dat alleen de directe veranderingen van het landgebruik zijn meegenomen, de potentiële indirecte landgebruiksveranderingen zijn niet gekwantificeerd. Potentiële broeikasgasemissies van indirecte landgebruiksverandering zijn sterk afhankelijk van de ontwikkeling van de agrarische sector in zijn geheel en het beheer van het landgebruik en kunnen vervolgens substantieel of minimaal zijn. Het bepalen van dergelijk landgebruik en de effecten van uitstoot van broeikasgassen vereist een andere aanpak.

Gegeven alle vooraf gedefinieerde suikerriet- en eucalyptus aanbodgebieden tot 2030 laten zien dat suikerriet een gemiddelde BKG uitstoot heeft van -80 kg CO_2/m^3 ethanol, terwijl de BKG emissie intensiteit van eucalyptus 1300 kg CO_2/m^3 is. Dit komt door het hoge aandeel bos dat naar eucalyptus plantages wordt omgezet. De hoge koolstofvoorraad van eucalyptus plantages in vergelijking met agrarisch land of grasland gecombineerd met hoge ethanolopbrengst, resulteert in een brede range van BKG-emissies van eucalyptus -3220 en 0 kg CO_2/m^3 ethanol. Anderzijds veroorzaakt de initiële koolstofvoorraad van bebost land grote BKG-emissie intensiteiten van ethanol geproduceerd door eucalyptus, variërend tussen 3,1 en 5,9 Mg CO_2/m^3 ethanol. Daardoor is de GHG-emissie intensiteit van ethanolproductie met behulp van eucalyptus in Goiás gemiddeld 1300 kg CO_2/m^3 ethanol, slechts ongeveer 30% lager dan de referentie fossielbrandstof (hoofdstuk 5). Omzetting van landbouwgrond resulteert in negatieve uitstoot van broeikasgassen, variërend tussen -570 en -100 kg CO_2/m^3 ethanol, aangezien de koolstofvoorraad van suikerrietplantage hoger is dan de koolstofvoorraad van landbouwgrond (echter zijn geen indirecte landgebruik effecten meegenomen). De omzetting van grasland resulteert in bescheiden broeikasgasemissies, 205-880 kg CO_2/m^3 ethanol, en de omzetting van bebost land resulteert in hoge broeikasgasemissies, variërend tussen 3150 en 5780 kg CO_2/m^3 ethanol, en is dus veel hoger dan fossiele benzine. Door de grote hoeveelheden agrarisch land omgezet naar suikerrietplantages, is de gemiddelde BKG-emissie intensiteit van ethanol in Goiás -80 kg CO_2/m^3 ethanol in tegenstelling tot de fossiele brandstof met een BKG emissie intensiteit van 1800 kg CO_2/m^3 (hoofdstuk 5). De directe verandering wordt berekend aan de hand over een periode van 20 jaar. Met andere woorden, de terugverdientijd van de koolstof is vastgesteld, de jaarlijkse koolstofvoorraadverandering is opgenomen in de emissie-intensiteit van de broeikasgassen. Dit zou betekenen dat na 20 jaar de uitstoot van landgebruik nul zal zijn.

Hoe kunnen economische prestaties van biobased toeleveringsketen voor de productie van elektriciteit, brandstof en chemicaliën uniform worden gekwantificeerd wat zijn de economische prestaties van regio-specifieke toeleveringsketen?

Om rekening te houden met het verschil in kosten en baten van een biomassa-plantage en de exploitatie van een industriële fabriek, wordt de netto-contante waarde (NPV) -aanpak algemeen gebruikt. Met behulp van een spreadsheet-model worden de economische prestaties van verschillende plantagebeheerstrategieën (hoofdstuk 3), ethanolproductieprocessen met verschillende biomassa-gewassen (hoofdstuk 4) en verschillende industriële verwerkingsroutes voor suikerriet- en eucalyptusverwerking (hoofdstuk 6) bepaald. De economische resultaten van hoofdstuk 4 zijn een belangrijke basis voor de optimalisatie van de biomassa keten in hoofdstuk 5.

De kosten van de houtlevering, zoals gekwantificeerd in hoofdstuk 3, omvatten de plantage beheerskosten (teelt), oogsten en transport naar een industriële faciliteit. De plantage beheerskosten van loblolly pine plantages worden bepaald voor elk jaar tijdens de plantage management cyclus, voor elk van de drie plantage management strategieën (conventioneel, extra uitdunning, korte rotatie). De kosten voor plantagebeheer worden toegewezen aan de hand van de potentiële prijzen van de onderscheiden houtklassen; zaaghout, chip-n-zaag, pulphout en residuen. Uit de resultaten blijkt dat het gebruik van de conventionele strategie resulteert in de laagste houtleveringskosten, 47 (46) US$/droge Mg-pulphout, voor bio-energie; kort daarna gevolgd door de extra uitdunningsstrategie, 50 (49) US$/Mg pulpwood. Het gebruik van de korte rotatie strategie heeft aanzienlijke hogere houtleveringskosten, 54 (52) US$/Mg pulphout met tussen haakjes de kosten wanneer ook residuen gebruikt worden). De leveringskosten van pulphout kunnen worden verdeeld in landkosten (17-22%), plantagebeheer (15-22%), oogsten (25-31%) en transport (31-37%).

Hoofdstuk 4 berekent bottom-up de huidige en toekomstige kostenstructuur van ethanolproductie geven de potentiele technische en economische ontwikkeling van biomassa teelt en industriële technologieën voor de eerste en tweede generatie ethanol productie. De kosten omvatten de kosten van biomassateelt, transport en industriële verwerking naar ethanol. De biomassa gewassen die bij deze studie zijn opgenomen zijn suikerriet, energycane, sweet sorghum, olifantengras en eucalyptus. De ontwikkeling van de totale ethanolproductiekosten (uitgedrukt in US$$_{2010}$/m^3 ethanol) van verschillende configuraties is bepaald (combinatie van biomassa gewas en industriële verwerkingstechnologie). Uit de resultaten blijkt dat de suikerriet- en energycane-cultivatiekosten in 2010 van 35 US$$_{2010}$/TC kunnen verminderen tot respectievelijk 27 US$$_{2010}$/TC en 22 US$$_{2010}$/TC. De kosten voor eucalyptus en olifantengras kunnen worden verminderd van 32 tot 23 US$$_{2010}$/ton nat en 38 tot 26 US$$_{2010}$/ton nat voor eucalyptus en olifantengras. De productiekosten van de eerste generatie ethanol kunnen afnemen door lagere gewaskosten, verhoging van het suikergehalte, het gebruik van suikerriet afval en het gebruik van sweet sorghum. Bovendien zijn de verbeteringen in industriële efficiëntie van het eerste generatie proces, het verhogen van de industriële schaal en het gebruik van een verbeterde technologie andere maatregelen om de productiekosten te verminderen. De totale ethanolproductiekosten van de eerste generatie verwerking kunnen in 2010 van 700 US$$_{2010}$/m^3 dalen tot 432 US$$_{2010}$/m^3 in 2030. Voor de tweede generatie technologie die gebruik maakt van eucalyptus, zouden de totale ethanolproductiekosten sterk kunnen dalen tot 424 US$$_{2010}$/m^3 in 2030. Kostenreductiemaatregelen voor de tweede generatie industriële verwerking omvatten verminderde gewaskosten, verhoging van de industriële efficiëntie en schaal en het inzetten van een meer geavanceerde industriële proces.

In hoofdstuk 5 is de verwachte uitbreiding van de ethanolproductiefaciliteiten in Goiás economisch geoptimaliseerd. Het BioScope optimalisatiemodel is gebruikt om de optimale locatie en schaal van de industriële verwerkingsfaciliteiten van suikerriet en eucalyptus te bepalen, gezien de geprojecteerde ruimtelijke verdeling van de biomassa leveringsgebieden in de staat Goiás tussen 2012 en 2030. De algemene modelleringsdoelstelling is om de totale ethanolproductiekosten voor alle biomassaleveringsgebieden in Goiás. Deze doelstelling omvat de kosten van land, biomassa teelt, biomassa transport en industriële verwerking. De industriële verwerkingskosten omvatten ook de potentiële opbrengsten van stroomoverschot. De gegevens over de beschikbaarheid van biomassa in de biomassa-voorzieningsregio's, de kostengegevens betreffende de teelt, het transport en de kapitaal- en operationele kosten van biomassaverwerking zijn exogeen bepaald en aan het BioScope optimalisatiemodel gevoed. De belangrijkste uitkomsten van het model zijn de locaties en de schaal van de industriële verwerkingsfaciliteiten en de hoeveelheid biomassa die wordt vervoerd van elke biomassaleveringsgebied naar bestaande en nieuwe industriële verwerkingslocaties. Deze resultaten worden gebruikt om de totale ethanolproductiekosten per biomassa-aanbodregio te berekenen. De geoptimaliseerde totale productiekosten van ethanol voor de verwerking van suikerriet zijn 894 US$$_{2014}$/m^3 ethanol in 2015 en dalen tot 202, 715 en 710 US$$_{2014}$/m^3 ethanol in 2030 voor respectievelijk meerdere-stappen, een-stap en volledig nieuw expansie. Voor eucalyptus dalen de ethanolproductiekosten van 635 US$$_{2014}$/m^3 in 2015 tot 560 en 543 US$$_{2014}$/m^3 in 2030 voor de verschillende-stap, een-stap en volledig nieuw expansie benadering. Deze kosten verschillen slechts marginaal voor de verschillende optimalisatiebenaderingen die werden gebruikt voor de 2030-

projecties door het gebruik van dezelfde biomassa-voorzieningsgebieden en de kleine variatie in de investeringskosten van industriële installaties. Door de ethanolproductiekosten voor de staat Goiás als geheel te optimaliseren, kunnen de schaal en locatie van individuele industriële verwerkingsinstallaties suboptimaal zijn voor een kleinere regio, maar ze maken deel uit van de optimale oplossing voor de gehele staat Goiás.

Hoofdstuk 6 heeft een verdisconteerde geldstroom spreadsheet gebruikt om de biobased productiekosten van de verschillende industriële verwerkingspaden te berekenen die ethanol, ethyleen, 1,3 propaandiol en barnsteenzuur produceren. De geldstromen omvatten de uitgaven voor suikerriet of eucalyptus gewas levering, investeringen, onderhoud, operationele kosten, arbeid en energiegebruik. Om een vergelijking mogelijk te maken tussen de verschillende biobased productiepaden en hun fossiele referentie wordt een uniforme aanpak en aannames toegepast. Voor deze vergelijking worden de productiekosten en de BKG emissiereductie uitgedrukt in respectievelijk US$/kg eindproduct en kg CO_{2eq}/kg eindproduct. Daarnaast wordt de vermindering van de uitstoot van broeikasgassen (met betrekking tot hun fossiele equivalentproduct) en potentiële totale winst per hectare grondstofteelt toegepast. Deze functionele eenheden zorgen voor een vergelijking tussen het gebruik van suikerriet of eucalyptus als biomassa grondstof.

Het bereik van biobased productproductiekosten met een 60% betrouwbaarheidsinterval is 0,64 - 1,10 US$/kg ethanol, 1,18 - 2,05 US$/kg ethyleen, 1,37 - 2,40 US$/kg 1,3 BOB en 1,91 - 2,57 US$/Kg barnsteenzuur. Alle biobased producten overlappen gedeeltelijk of volledig met de productiekosten van de fossiele equivalente producten. Uit de resultaten blijkt dat suikerriet op basis van 1,3 PDO en in mindere mate de productie van barnsteenzuur het hoogste economische potentieel heeft voor grootschalige industriële productie. Bij een olieprijs van 50 dollar per vat hebben de ethanol- en ethyleenproductiepaden het moeilijk om te concurreren met de prijs van fossiele producten, terwijl de productie van 1,3 PDO en barnsteenzuurproductie uit suikerriet en de productie van eucalyptus-barnsteenzuur winstgevend zijn. In de economische beoordeling in deze studie wordt geen rekening gehouden met de mogelijke impact van belastingen, belastingvrijstellingen of premies die betaald voor biobased producten. De variatie in prijzen van petrochemische producten is gebaseerd op een variatie in de ruwe olieprijs tussen 40 en 130 US$/vat. Met de huidige olieprijzen van 50 US$/vat zijn de meeste biobased productiepaden niet concurrerend, maar stijgende olieprijzen kunnen de economische levensvatbaarheid verhogen.

Uit de evaluaties van de economische prestaties van regio-specifieke biobased leveringsketens blijkt dat de kosten voor de biomassa gewassen over het algemeen het grootste aandeel hebben in de totale ethanolproductiekosten. Voor de productiekosten van de eerste generatie ethanolproductie zijn de biomassa de grootste bijdrage aan de totale ethanolproductiekosten. Voor de ethanolproductie van de tweede generatie zijn kosten voor biomassa levering belangrijk, maar ook de afschrijving en de kosten voor de enzymen spelen een prominente rol. Voor biobased chemicaliën zijn de kapitaalafschrijving en energie nog prominenter. Dit komt voornamelijk uit de kapitaalinvestering en het energieverbruik in verband met het productextractie en zuivering van biobased chemicaliën na de fermentatiestap.

Wat zijn de afwegingen tussen de BKG balans en de economische prestaties van verschillende biomassa ketens voor verschillende regio's?

Voor naaldbosplantages in de VS illustreert hoofdstuk 2 duidelijk dat de koolstof terugverdientijden drastisch kunnen worden verminderd door de verhoogde biomassa opbrengsten door intensief beheer. Echter, met de huidige marktprijzen voor houtproducten, zijn dergelijke strategieën momenteel niet economisch interessant. De afwegingen tussen de economische prestaties en de uitstoot van broeikasgasemissies worden ook in hoofdstuk 3 geïllustreerd, aangezien dit hoofdstuk gelijktijdig de kosten en de totale koolstofbalans van verschillende naaldbos beheerstrategieën kwantificeert. Het overschakelen van de huidige conventionele plantagebeheerstrategie zonder het gebruik van residuen voor bioenergie naar een extra uitdunningsstrategie met gebruik van residuen verhoogt de totale koolstofbalans met ongeveer 31%, tegen een marginale hogere houtleveringskosten. In vergelijking met de andere strategieën heeft de extra uitdunstrategie de hoogste totale houtopbrengst, waarvan een groot deel is geclassificeerd als chip-n-zaag en zaaghout. De opbrengst van de hogere waarde houtklassen van de extra uitdunstrategie levert ook de laagste cultivatiekosten op voor pulphout en residuen (indien van toepassing), waardoor deze strategie het meest economisch aantrekkelijk is voor boseigenaren. Bosbezitters moeten echter decennia vooraf beslissen over plantstrategieën voordat ze de voordelen van een gewijzigde managementstrategie kunnen halen. Gezien de onzekere beloning (of niet) die de boseigenaren kunnen ontvangen voor extra koolstofafgifte, is het twijfelachtig of de grondeigenaren daadwerkelijk de risico's die bij deze omschakeling spelen, zullen accepteren.

Een mogelijkheid om de extra kosten af te zetten tegen de extra koolstofopslag van de verschillende plantagebeheerstrategieën is om ze uit te drukken als CO_2-kosten. Koolstofdioxide kosten worden berekend voor de plantage management strategieën met behulp van het verschil in zowel de totale koolstofbalans als de plantage beheerskosten in vergelijking met de conventionele strategie. Zoals blijkt uit tabel 3-9 van hoofdstuk 3, variëren de kosten van additionele CO_2-vastlegging tussen -13 en 21 US$/Mg CO_2. Dit illustreert dat in sommige gevallen win-win situaties kunnen optreden, terwijl in andere gevallen kosten zijn verbonden aan extra koolstof vastlegging.

Andere afwegingen komen voor in de economische prestatie of binnen het BKG-balans:

- De stijging van de biomassa-opbrengst lijkt een duidelijke optie om de kosten te verminderen (en meestal ook de uitstoot van broeikasgassen), maar de stijging van de droge stof mag niet ten koste gaan van gunstige biomassa eigenschappen, zoals het suikergehalte van suikerriet of het glucan-gehalte van lignocellulose biomassa, indien het wordt omgezet via een biochemische omzettingsroute. Bovendien kunnen ook transportkosten worden verlaagd als de biomassa opbrengst toeneemt, maar dit heeft slechts een marginale impact op de totale productiekosten (Hoofdstuk 4).

- Hoofdstuk 5 laat zien dat grootschalige industriële verwerking in een gebied de voorkeur geniet door geclusterd biomassa aanbod, lage transportkosten en schaalvoordelen voor industriële verwerking. In meerdere gevallen is de maximaal toegestane schaal (zoals in het optimalisatiemodel) van industriële installaties bereikt. Optimale locaties verschillen onder de verschillende expansie benaderingen die gebruikt worden. In de meeste gevallen hebben industriële installaties de voorkeur in hoge opbrengstgebieden voor biomassa om de gemiddelde transportkosten te reduceren.
- Hoofdstuk 6 beschouwt de BKG emissie intensiteit en mogelijke winst van 4 eindproducten met behulp van verschillende literatuur bronnen. Een belangrijk resultaat is dat de industriële verwerkingspaden die suikerriet gebruiken, aantonen een hogere BKG-emissiereductie en potentiële nettowinst hebben in vergelijking met het gebruik van eucalyptus. Suikerriet omzetten naar 1,3 PDO heeft de hoogste winstmarge (3211 US$/ha-jaar) en reductie van broeikasgasemissies per kg biobased product (5,2 kg CO_2/kg). De barnsteenzuurproductie heeft echter een hogere BKG-emissiereductiepotentieel per hectare; 41 Mg/ha-jaar voor vergeleken met 33 Mg/ha-jaar voor 1,3 PDO. In vergelijking met hun fossiele referentie hebben biobased ethanol en ethyleen de hoogste relatieve BKG-emissiereductie, hoewel hun economische prestaties minder concurrerend zijn. Deze voorbeelden illustreren dat het bepalen van 'optimale' biobased productiepaden afhangt van de gekozen optimalisatie-doelstelling (economische winst, reductie van BKG-emissies of beide) en de gekozen eenheid om de economische en BKG-prestaties te bepalen.

8.4 Kernboodschappen en aanbevelingen

Kernboodschappen

De terugverdientijden van de koolstofschulden en pariteitsperiode kunnen actief verkort worden door slimme beheer strategieën te kiezen en de vermijdingseffecten van geoogst hout te maximaliseren. De terugverdienperiode van de koolstofschuld en de CO_2-pariteitsperiode worden beïnvloed door de opbrengst van biomassa, koolstofsubstitutiefactor, systeemgrenzen en de keuze van het referentiescenario. In dit proefschrift blijkt dat de overstap naar zeer productieve plantages de opname van koolstof sterk verhoogt, waardoor de extra uitstoot van bosbouwpraktijken verreweg teniet gedaan wordt. Uitgaande van de resultaten in hoofdstuk 3 kan echter geconcludeerd worden dat de totale opbrengst van het houtvolume niet per se het beste criterium is voor de selectie van de beste plantagebeheerstrategieën om koolstof te verzamelen. De plantagebeheerstrategie die hoge hoeveelheden zaaghout en chip-n-zaaghout levert, vermijdt meer broeikasgasemissies, vooral voor de langere termijn. Om een hoge koolstofsubstitutie te bereiken is de wisselwerking tussen de geoogste houtopbrengst en de bijbehorende koolstofsubstitutie van het geoogste hout belangrijk.

De productiekosten van ethanol in Brazilië kunnen in de toekomst aanzienlijk worden verminderd. De ethanolproductiekosten van de eerste generatie industriële productie kunnen afnemen door verminderde biomassakosten, verhoogd suikergehalte en opschalen van industriële faciliteiten. Het gebruik van geoptimaliseerde technologie, het verzamelen en gebruiken van suikerriet afval en het gebruik van sweet sorghum verlaagt de productiekosten van ethanol nog verder. Voor de tweede generatie industriële verwerking zijn de verminderde biomassakosten, stijging van de industriële efficiëntie, opschalen en het gebruik van geoptimaliseerde technologie factoren om de productiekosten van ethanol te verminderen. In totaal is de totale kostenverlaging in deze studie 48%, 41% en 53% voor de eerste generatie, geïntegreerde eerste en tweede generatie en tweede generatie industriële productie. In het algemeen kan de productie van tweede generatie ethanol met behulp van eucalyptus resulteren in de laagste ethanolproductiekosten in 2030.

De uitstoot van broeikasgassen door direct landgebruiksverandering kan de BKG-emissie intensiteit van de ethanolproductie zowel positief als negatief beïnvloeden. Wanneer er agrarisch land wordt omgezet naar suikerriet, kan koolstof worden vastgelegd in zowel bodem- als biomassa-koolstof. Dit draagt bij aan een hoog BKG-emissiereductiepotentieel van suikerriet ethanol. Het BKG-emissiereductiepotentieel van ethanol kan echter volledig verdwijnen als een gebied met hoge koolstofvoorraden omgezet wordt. Daarom verandert de BKG-prestatie van biomassa-ketens sterk met locatie van biomassa cultivatie en de daarbij horende landgebruiksveranderingen.

Biobased chemische producten kunnen winstgevend zijn en kunnen een aanzienlijke reductie van broeikasgasemissies behalen - maar het bepalen van een winnaar is complex. De gerapporteerde kostenbereiken van de biobased producten overlappen gedeeltelijk met de bereiken van hun fossiele referentieproducten. Suikerriet-1,3 PDO en de productie van barnsteenzuur geeft de hoogste economische prestatie. De kosten van deze productiepaden zijn echter onzekerder in vergelijking met de meer conventionele ethanol- en ethyleenproductie. De reductie van broeikasgasemissies per kg biobased product verschilt aanzienlijk: BKG besparingen tussen 3 en 105% zijn gekwantificeerd. Over het geheel genomen was het niet mogelijk om een duidelijke winnaar te kiezen, aangezien: a) het best presterende product sterk afhankelijk is van de gekozen indicator, en b) het grote bereik in de productiekosten en de broeikasgasemissie uitstoot, met name voor PDO en barnsteenzuur, onafhankelijk van de gekozen indicator.

Aanbevelingen voor de industrie en beleidsmakers

- Om de koolstof terugverdientijd en de koolstofcompensatiestijd te kwantificeren, zijn de selectie van methodologische perspectieven en de keuze van het referentiescenario belangrijke factoren. Bovendien zijn de groeisnelheid van het bos en de koolstofsubstitutie belangrijke elementen. Met dit gegeven kunnen de koolstofterugverdientijden actief en significant verminderd worden met beheerstrategieën die zowel rendement optimaliseren alsook houtproducten produceren met hoge koolstofsubstitutie. Sommige van deze strategieën (bijvoorbeeld het verhogen van de initiële aanplantdichtheid) kunnen al

economisch levensvatbaar zijn; Anderen (bijv. verhoging van de totale opbrengsten) vereisen bijkomende beleidsondersteuning. Een verandering van het plantagebeheer, om meer koolstof vast te leggen, zou echter een investering in de toekomst vereisen. Daarom moet steun voor plantage-eigenaren consistent zijn en rekening houden met de plantagecyclus tijd.
- Voor biomassa-gewassen lijkt de toename van de biomassa-opbrengst een duidelijke optie om de kosten te verminderen, maar de stijgende opbrengst mag niet ten koste gaan van gunstige eigenschappen, zoals het suikergehalte van suikerriet of het glucangehalte van lignocellulose-biomassa. Het suikergehalte van suikerriet is een van de belangrijkste verbeteringsopties van de productie van de eerste generatie ethanol. Daarom moet de verbetering van de oogst in overweging worden genomen met de (verwachte) vraag naar biomassa-gewasspecificaties.
- Veel van de analyses die in deze studie zijn uitgevoerd, beschouwen de n^{de} plant technologie. De ontwikkeling van nieuwe industriële verwerkende technologieën, zoals de tweede generatie en biobased chemicaliën productie, vereisen echter aanzienlijke investeringen in onderzoek en ontwikkeling en opschalen voordat dergelijke grote productiefaciliteiten gebruikt kunnen worden. Daarom lijkt een radicale verschuiving naar nieuwe industriële verwerkingsopties minder waarschijnlijk.
- De keuze van het optimale inzet van biomassa is niet eenvoudig omdat de prestaties uitgedrukt kunnen worden in verschillende indicatoren, elk met een andere rangschikking van de biomassa configuraties. Daarom kunnen duidelijke richtlijnen voor de indicatoren de vergelijking en selectie optimale biomassa-gebruiksopties ondersteunen.

<u>Aanwijzingen voor verder onderzoek</u>

De economische en BKG-prestaties van verschillende biomassa-ketens worden gekwantificeerd voor de productie van houtpelletjes in het Zuidoosten van de VS en ethanolproductie in Brazilië. De ex ante-analyses die in dit proefschrift worden gebruikt, bieden een beter gefundeerde inzicht in de potentiële ontwikkelings- en implementatiestrategieën voor de inzet van biomassa in de toekomst. Toekomstige analyses van de totale BKG balans van biomassa-ketens vereisen gedetailleerder kwantificering van de volgende elementen:

- het belang van koolstofvoorraadverandering; Ofwel de initiële koolstofvoorraadverandering van bosbouwbiomassa of de verandering van de koolstofvoorraad door de verandering van het landgebruik voor biomassa-gewasproductie. Dit omvat een gedetailleerde beoordeling van waar dit direct en eventueel ook de indirecte landgebruiksverandering zou plaatsvinden.
- Voor bosbouwbiomassa is meer informatie nodig over het effect van managementpraktijken, met inbegrip van residu collectie en gebruik voor bio-energie, op de verschillende koolstof voorraden. Vooral de relatie tussen verhoogde houtwinning en bodem organische koolstof is niet goed begrepen.

- Meer gedetailleerde informatie over de groei van de bossen, met name de groeisnelheid en de koolstofsubstitutiefactoren, zullen de robuustheid van de resultaten van de economische analyse en vooral de koolstofbalans kunnen verbeteren.
- Het gebruik van meststoffen speelt een belangrijke rol in de broeikasgasemissies van suikerriet-, eucalyptus- en naaldhout biomassa gebruik. Meer kennis over het toepassing van meststoffen, de verhouding tussen de biomassagroei en de toepassing van meststoffen, en de optimalisatie van het gebruik van meststoffen kan bijdragen tot het verminderen van de impact van meststoffen op de totale BKG-balans van biomassa-ketens.
- Naaldhout wordt vooral gebruikt om houtpellets te produceren voor de warmte- en elektriciteitsmarkt. Koolstof terugverdientijden van potentiële geavanceerde andere producten van naaldhout (bijvoorbeeld 2e generatie biobrandstoffen en duurzame bioplastics) moeten ook worden onderzocht om optimale BKG mitigatie strategieën te identificeren.
- Voor tweede generatie ethanolproductie en de productie van biobased chemicaliën is het gebruik van proces-energie onzeker. Betere gegevens over het gebruik van procesenergie zouden de bepaling van de GHG-emissiebalans van deze producten verbeteren.

Om de inzichten in de economische prestaties en de robuustheid van de resultaten te verbeteren, moet toekomstig onderzoek zich richten op:

- Biomassa-opbrengst reageert op bodemkwaliteit, klimaatomstandigheden en intensiteit van de plantagebeheer. Een betere kwantificering van de biomassa opbrengst in relatie tot deze site en case-specifieke kenmerken kan de onzekerheid van het biomassa-opbrengstniveau verminderen, en zo de robuustheid van de economische analyse verbeteren. Bovendien zijn het gebruik van plantagebeheer-, oogst- of verwerkingsresiduen belangrijk voor de economische prestaties. Meer inzicht is nodig in de kosten die verband houden met de mobilisatie en het gebruik van deze residuen als grondstof voor biomassa-ketens.
- Meer gedetailleerde kwantificering van de conversie-efficiëntie van geavanceerde bioraffinage processen, gebaseerd op inzichten van pilot- of demonstratieprojecten van biobased chemicaliën, vermindert de onzekerheden in de toekomstige economische analyse van grootschalige industriële productie.
- Een meer gedetailleerde analyse van de kosten van apparatuur, schaalfactoren, maximumschaal en totale investeringskosten van de verschillende industriële verwerkingsstappen zou de robuustheid van de totale investeringskosten van geavanceerde bioraffinage processen verbeteren.
- Meer inzicht in de input en vooral het energieverbruik van nieuwe industriële processen voor de fermentatie en extractie van nieuwe biobased producten, waaronder industriële processen met meerdere hoofdproducten en meer complexere bioraffinageconcepten.

De verschillende hoofdstukken van dit proefschrift tonen het belang en de impact van de inbedding van biomassa-ketens in de reeds bestaande landgebruiks- en biomassa-gebruikssectoren. Aangezien in dit proefschrift vooral de focus gericht was op bioraffinage met een of twee hoofdproducten, zou verder onderzoek moeten richten op de integratie van verschillende biomassa-gebruiksopties, multi-input industriële processen of co-productie van verschillende producten voor de potentiële mogelijkheden voor de toekomstige inzet. Integratiestrategieën kunnen de kosten of broeikasgasemissies verminderen, maar ook leiden tot gecombineerde voordelen met betrekking tot het efficiënte gebruik van landbouwgrond of bosplantages. Een belangrijk element in dergelijke analyses is de mogelijke invloed op de marktprijzen van biochemische stoffen op het moment dat biobased chemicaliën een hoge marktpenetratiegraad bereiken. Ook het gecombineerde en ex ante gebruik van de methodes die in het proefschrift in de opkomende biomassegebieden zijn aangetoond, kunnen beter inzicht geven in optimale ontwikkel- en implementatie-strategieën voor biobased economie opties over de tijd.

Ten slotte richtte dit proefschrift zich uitsluitend op de economische en GHG-prestaties van verschillende biomassa-ketens. Andere aspecten, zoals algemene milieueffecten (bijv. op biodiversiteit, vereist om duurzame beheerscriteria te behalen) en sociaal-economische impact (bijv. eventueel bijkomende werkgelegenheid) moeten verder worden onderzocht. Daarom is meer onderzoek en beleidsfocus gewenst over hoe biomassa productie systemen en waardeketens optimaal kunnen worden gecombineerd met betere grondgebruikstrategieën, met inbegrip van efficiëntere en duurzame landbouw- en bosbouwpraktijken. Dergelijke strategieën kunnen niet alleen biomassa productie en implementatie optimaliseren, maar kunnen ook leiden tot gecombineerde voordelen met betrekking tot meer hulpbronnen (land, water, voedingsstoffen) efficiënte landbouw en veerkrachtige bossen.

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Curriculum vitea

Gert-Jan Jonker was born on the 1st of September 1986 in Nijkerk, The Netherlands. He studied mechanical engineering at the Hogeschool Utrecht (2003-2007). His BSc thesis focussed on the design and operational conditions of earth energy systems. Prior to his master's study he worked for 7 months for Geotherm Energy Systems. He then started the master program Energy Science at Utrecht University. The focus of his MSc thesis was on the economic performance and energy balance of micro-algae systems for the production of heat, electricity and fuels.

Gert-Jan started as a junior researcher at the Copernicus Institute for Sustainable Development at Utrecht University in 2010. After a period as junior researcher he started as a PhD student for the BE-Basic project. The research focussed on the societal embedding of biobased supply chains, more specifically, Gert-Jans research included the economic performance, carbon balance and GHG emission intensity of biomass supply chains. This work has resulted in five peer-reviewed publications and different conference presentations. His submission to the European Biomass Conference and Exhibition in Vienna 2015 was rewarded with a student award for excellent research work in the field of biomass. In addition, Gert-Jan has supervised Master student thesis projects and has been a teaching assistant for the Energy Science Masters programme.

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