Environmental assessment of biomass based materials

With special focus on the climate effect of temporary carbon storage

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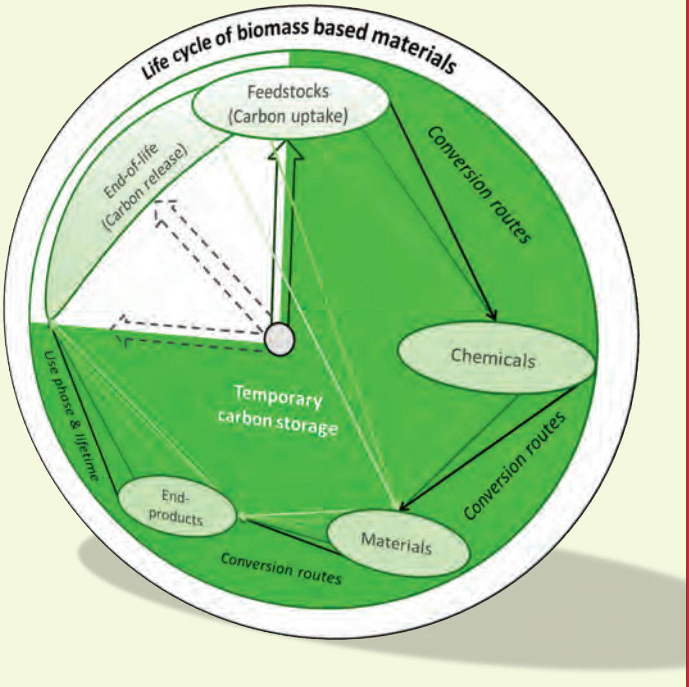

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DTU Management Engineering
Department of Management Engineering

Environmental assessment of biomass based materials

- With special focus on the climate effect of temporary carbon storage

Susanne Vedel Jørgensen

Industrial PhD Dissertation

Department of Management Engineering

Technical University of Denmark

Corporate Sustainability

novozymes

To my family, for your encouragement and support
And to Thomas, for your backing and patience through the run-up phase

Preface

This dissertation is the outcome of an industrial PhD project performed in collaboration between Novozymes A/S and the Department of Management Engineering at the Technical University of Denmark. The title of the project is: *Environmental assessment of biomass based materials - With special focus on the climate effect of temporary carbon storage*. The project was initiated in November 2010 and finalized in January 2014.

The dissertation includes four articles, which all have been published in peer-reviewed journals and can be seen in Chapter 14. Further, the dissertation includes a report introducing, summarizing and concluding on the outcome of the articles, as well as additional chapters for introducing other areas relevant for drawing overall conclusions.

Professor Michael Zwicky Hauschild, head of division, Division for Quantitative Sustainability Assessment (QSA), DTU Management Engineering has been the university supervisor, while Senior Manager Per Henning Nielsen, Novozymes A/S has been the company supervisor. Jesper Hedal Kløverpris, Sustainability Manager, Novozymes A/S has been co-supervisor from the company.

The PhD project was defended in April 2014 at the Technical University of Denmark. Since then, only minor changes have been made to the dissertation. The only textual changes are, that the published versions of all articles are now included in the printed version of the dissertation, and the publication years and links to the published articles have been included in both the online and the printed version of the dissertation.

Susanne Vedel Jørgensen

Acknowledgments

From the project proposal to the finalizing of the PhD project, many people have contributed in various ways, for which I am thankful. First, I want to thank my two main supervisors, Professor Michael Zwicky Hauschild (Technical University of Denmark) and Senior Manager Per Henning Nielsen (Novozymes), for their interest in entering into the project with me and for their guidance and advice along the way, from which I have learned a lot. Also thanks to my co-supervisor, Sustainability Manager Jesper Hedal Kløverpris (Novozymes), for scientific discussions and for sharing experiences and advice with respect to being an industrial PhD student, which has been greatly appreciated. Further, thanks to all of my great colleagues, both at the Technical University of Denmark and at Novozymes, for scientific discussions, constructive feedback, moral support and three great years with lots of good experiences.

Also a special thanks to those who welcomed me for abroad research stays of different lengths: Researchers Ottar Michelsen and Francesco Cherubini (Norwegian University of Science and Technology, Department of Energy and Process Engineering, Industrial Ecology Program) and Assistant Professor Daniel Johansson (Chalmers University of Technology, Department of Energy and Environment, Division of Physical Resource Theory).

Finally, thanks to Novozymes for employing me during the PhD project, and to the Danish Agency for Science, Technology and Innovation, for co-funding this industrial PhD project.

Summary

Goal and scope

The goal of this PhD project is to contribute to a more consistent methodology for life cycle assessment (LCA) of biomaterials and to address the environmental performance and perspectives of biomaterials. In particular, it is the goal to develop an approach for dealing with temporary carbon storage in biomaterials, in a way that quantifies the potential climate change benefit in relation to avoiding crossing near-term climatic targets.

The geographical scope in this PhD project is global, as the focus is on methodology development and assessment of biomaterials at a global level. The temporal scope is defined by the impact category considered. The technological scope includes both current environmental performance of biomaterials and a discussion of future perspectives, including potentials for future change in their environmental impacts compared to fossil based materials.

Background

The society today is highly dependent on fossil oil and gas for producing fuels, chemicals and materials, however many of those can alternatively be produced from biomass. The potential of biomaterials to substitute fossil based materials receives increased attention, and their global production is increasing. As the demand for biomaterials increases, so does the need for knowledge about their environmental performance – both in absolute terms and relative to the petrochemical counterparts that they may replace. LCA is a commonly used tool for assessing environmental sustainability of products and systems, accounting for the environmental impacts during their entire lifecycle. However, there are still important gaps in the methodology for LCAs of biomaterials.

One such gap is the handling of the potential climate change mitigation value of the temporary storage of carbon that takes place in biomaterials, on which there is currently no consensus. Other important environmental aspects related to biomaterials that are currently not generally included in LCAs are land use and land use change (LULUC) related impacts, such as changes in biogenic carbon stocks (especially including soil organic carbon), surface albedo and biodiversity, as well as potential indirect land use changes (ILUC) of biomaterial production.

Potential value of (temporary) carbon storage

Due to the existence of climate tipping points, expected to induce dangerous and potentially irreversible changes in the climate system if crossed, temporary carbon storage may have a potential for contributing to mitigating climate change. This potential is in terms of either avoiding the crossing of such expected tipping points (assuming the mitigation scenario RCP3PD, where the atmospheric CO_2 concentration peaks within the coming decades) or substantially postpone the crossing (assuming the medium stabilization level scenario RCP6 with a continuous growth in the atmospheric CO_2 concentration towards year 2100).

Besides the value of the temporary carbon storage in single products, resulting stock changes are expected if petrochemical materials are substituted with biomaterials. These stock changes are more long-term or even permanent, leading to a reduction of carbon fluxes from fossil resources, while potentially increasing fluxes from the atmosphere to the biosphere and via this to the anthroposphere. This leads to a decrease in atmospheric carbon stock and increase in biosphere carbon stock, as well as an increase of biogenic carbon storage in the anthroposphere. This is a trend that will be permanent as long as the biomaterial production is not decreased or phased out again.

The CTP approach

The general used metric in LCA for assessing climate change, the GWP, does not take into account the need for staying below climatic target levels, and it does not reflect the increased importance of short-lived GHGs in terms of near-term target levels.

An approach has been developed in this PhD project for inclusion of the urgency of avoiding crossing dangerous climatic tipping points in the assessment of GHG emissions – the Climatic Tipping Potential (CTP). This approach assesses impacts of GHG emissions up until the potential crossing of a predefined climatic target level. This impact is expressed as a fraction of the atmospheric ‘capacity’ for absorbing the impact without exceeding the target level. The CTP should be seen as complementary to GWP, which should still account for long-term climate change impacts.

The CTP method has been further developed to consider the aspect of temporary carbon storage, and illustrate the potential mitigation value of this in relation to avoid crossing dangerous climatic target levels. CTP characterization factors for several GHG development scenarios and a number of other important model parameters are given, making the approach operational for direct inclusion in LCA.

Influence of selected non-standard impacts from land use and land use change (LULUC)

Some of the impacts associated with LULUC for biomass production, which are often not addressed in LCAs have been addressed through a theoretic case study in this PhD project. These impacts are changes in surface albedo, biogenic carbon fluxes (including SOC) and biodiversity. All three impacts are here found to be potentially important for the environmental performance of the biobased production. Further, potential tradeoffs are found between these impacts. This supports the need for including the best possible assessment of these impacts in LCA, in order to get a realistic picture of the overall impacts from a biomass feedstock crop establishment, and thus downstream products. However, there is a challenge in terms of e.g. the preliminary state of methods, and the requirements to availability of local data.

Available biomass potential

When discussing the environmental preference of biomaterials relative to fossil-based materials, an important aspect is the sustainable availability of biomass for the production of the biomaterials. It is estimated that there will be enough biomass feedstock available for future biomaterial production without competing with food for the land, even if the entire global need for organic chemicals (including polymers) is based on biomass in the future. However, there is likely to be a competition with bioenergy, including biofuels, for the biomass.

Environmental performance of biomaterials

Biomaterials generally perform better than equivalent petrochemical materials in terms of fossil fuel savings and reductions in GHG emissions. However in other impact categories they often perform worse, e.g. in terms of eutrophication and acidification, while also entailing land use and related environmental impacts. If using second generation biomass, some of those aspects are likely to improve. It is important to understand that the group of biomaterials is very diverse, both in terms of life cycle pathways and end-products. This gives different environmental profiles within the group, and one should thus be careful with a ‘one profile fits all’ mindset when it comes to environmental assessment of biomaterials.

Future perspectives

As biomaterials are often based on new, and hence immature, technologies, large improvement potentials are expected for those technologies relative to the competing petrochemical technologies, which are rather mature. Further, potential future shifts in feedstock for both biomaterials and fossil based materials may change their relative environmental performance.

Resumé

Mål og afgrænsning

Målet med dette PhD-projekt er at bidrage til en mere konsistent metode til livscyklusvurdering (LCA) af biomaterialer og at adressere den miljømæssige præstation samt perspektiver af biomaterialer. I særdeleshed er det målet at udvikle en metode til at håndtere midlertidig kulstoflagring i biomaterialer, på en måde der kvantificerer mulige klimaforandrings-’gevinster’ i forhold til at undgå at overskride nært forestående klimatiske grænseniveauer.

Den geografiske afgrænsning i dette PhD-projekt er global, da fokus er på metodeudvikling og vurdering af biomaterialer på globalt plan. Den tidsmæssige afgræsning er defineret af den miljøpåvirkningskategori som tages i betragtning. Den teknologiske afgrænsning omfatter både aktuelle miljømæssige præstationer af biomaterialer og en diskussion af fremtidige perspektiver, herunder potentialer for fremtidig ændring i deres miljøpåvirkninger i forhold til fossile materialer.

Baggrund

Nutidens samfund er i høj grad afhængigt af fossil olie og gas til fremstilling af brændstof, kemikalier og materialer, men mange af disse kan alternativt produceres af biomasse. Biomaterialers potentiale i forhold til at erstatte fossile materialer får øget opmærksomhed og den globale produktion af biomaterialer er stigende. Med den stigende efterspørgsel efter biomaterialer følger et stigende behov for viden om deres miljømæssige præstationer – både absolutte og i forhold til de tilsvarende petrokemiske materialer de kan erstatte. LCA er et almindeligt anvendt værktøj til miljøvurdering af produkter og systemer, som tager højde for miljøpåvirkningerne gennem hele deres livsforløb. Der er dog stadig betydningsfulde huller i metodegrundlaget for LCA’er af biomaterialer.

Et sådant hul er håndteringen af værdien af den potentielle afbødning af klimaforandringer fra den midlertidige kulstoflagring som finder sted i biomaterialer, hvor der på nuværende tidspunkt ikke er konsensus. Andre vigtige miljøaspekter i forbindelse med biomaterialer, som i øjeblikket generelt ikke medtages i LCA, er påvirkninger relateret til arealanvendelse og ændringer i arealanvendelse (LULUC), såsom ændringer i biogene kulstoflagre (især inkluderende organisk kulstof i jorden), overflade albedo og biodiversitet, samt potentielle indirekte ændringer i arealanvendelse (ILUC) som følge af produktion af biomaterialer.

Potentiel værdi af (midlertidig) kulstoflagring

Som følge af eksistensen af klimatiske ’tippe-punkter’ (’tipping points’), som forventes at forårsage farlige og potentielt irreversible ændringer i klimasystemet hvis de overskrides, kan midlertidig kulstoflagring have et potentiale i form af at bidrage til at afbøde klimaændringerne. Dette potentiale er i form af at enten at undgå overskridelse af sådanne forventede tippe-punkter (forudsat at der bliver tale om ’afbødningsscenariet’ RCP3PD, hvor den atmosfæriske CO_2-koncentration topper indenfor de kommende årtier) eller væsentligt udskyde overskridelsen (forudsat at der bliver tale om ’medium-stabiliseringsniveau-scenariet’ RCP6, hvor den atmosfæriske CO_2-koncentration fortsætter med at stige frem mod år 2100).

Udover værdien af midlertidig kulstoflagring i enkeltprodukter forventes resulterende ændringer i kulstoflagre, hvis petrokemiske materialer bliver erstattet af biomaterialer. Disse ændringer i kulstoflagre er mere langsigtede eller endda permanente, hvilket leder til en reduktion i kulstofstrømme fra fossile ressourcer, mens kulstofstrømme fra atmosfæren til biosfæren, og via denne til antroposfæren, potentielt forøges. Dette leder til en reduktion af mængden af kulstof lagret i atmosfæren, samt en forøgelse af den biogene kulstoflagring i antroposfæren. Denne tendens vil være permanent så længe biomaterialeproduktionen ikke formindskes eller udfases igen.

CTP-tilgangen

Den generelt anvendte tilgang til vurdering af klimaændringer i LCA, GWP, tager ikke hensyn til behovet for at forblive under klimatiske grænseniveauer og den afspejler ikke den øgede betydning af kortlivede drivhusgasser i forhold til nært forestående grænseniveauer.

En metode til inddragelse af haste-aspektet i forhold til at undgå overskridelse af farlige klimatiske tippe-punkter ved vurdering af drivhusgasemissioner, det ’klimatiske tippe-potentiale’ (CTP) er blevet udviklet i dette PhD-projekt. Denne metode vurderer påvirkningerne af drivhusgasemissionerne frem til den potentielle overskridelse af et foruddefineret klimatisk grænseniveau. Denne påvirkning udtrykkes som en brøkdel af den atmosfæriske kapacitet til at absorbere påvirkningen uden at overskride grænseniveauet. CTP skal ses som et supplement til GWP, som fortsat skal gøre rede for de langsigtede klimapåvirkninger.

CTP-metoden er desuden blevet videreudviklet til at tage højde for aspektet omkring midlertidig kulstoflagring og illustrere den potentielle afbødningsværdi af denne i forhold til at undgå overskridelse af farlige klimatiske grænseniveauer. CTP-karakteringsfaktorer for flere drivhusgasudviklingsscenarier og en række andre vigtige modelparametre er fremført, hvilket gør metoden anvendelig til direkte inklusion i LCA.

Indflydelse af udvalgte ikke-standard påvirkninger fra arealanvendelse og ændringer i arealanvendelse (LULUC)

Nogle af de påvirkninger der er forbundet med arealanvendelse og ændringer i arealanvendelse i forbindelse med produktion af biomasse, som generelt ikke medtages i LCA’er, er blevet adresseret via et teoretisk case study i dette PhD-projekt. Disse påvirkninger er ændringer i overflade albedo, biogene kulstofstrømme (inklusiv organisk kulstof i jorden) og biodiversitet. Alle tre typer påvirkning er her fundet at være potentielt vigtige for miljøpræstationen af den biobaserede produktion. Endvidere er der fundet potentielle kompromiser i mellem de forskellige typer miljøpåvirkninger. Dette understøtter behovet for at inkludere den bedst mulige vurdering af disse påvirkninger i LCA, for at få er realistisk billede af de samlede konsekvenser fra etablering af en biomasseråstof-afgrøde, og dermed af afledte produkter. Men der er en udfordring i form af eksempelvis metoder som er på et indledende niveau, samt kravene til tilgængelighed af lokale data.

Tilgængeligt biomassepotentiale

Når miljøfordelene ved biomaterialer relativt til fossilt-baserede materialer diskuteres er et vigtigt aspekt den bæredygtige tilgængelighed af biomasse til produktionen af biomaterialerne. Det anslås, at der vil være nok biomasseråstof til rådighed for fremtidig biomaterialeproduktion uden at konkurrere med fødevareproduktion om jorden, selv hvis hele det globale behov for organiske kemikalier (inklusive polymerer) baseres på biomasse i fremtiden. Men sandsynligvis vil der være en konkurrence med bioenergi, herunder biobrændstoffer, om biomassen.

Miljøpræstationer af biomaterialer

Biomaterialer klarer sig generelt bedre end tilsvarende petrokemiske materialer når det kommer til fossil brændstof besparelse og reduktioner i drivhusgasudledninger. Men i andre miljøpåvirkningskategorier klarer de sig ofte dårligere, f.eks. med hensyn til eutrofiering og forsuring, mens de også medfører arealanvendelse og hertil relaterede miljøpåvirkninger. Hvis der benyttes anden generations biomasse vil nogle af disse aspekter sandsynligvis forbedres. Det er vigtigt at forstå, at gruppen af biomaterialer er meget forskelligartet, både med hensyn til livscyklusveje og slutprodukter. Dette fører til forskellige miljøprofiler internt i gruppen af biomaterialer, og man skal derfor passe på med en 'én profil passer alle'-tankegang når det kommer til miljøvurdering af biomaterialer.

Fremtidige perspektiver

Da biomaterialer ofte er baseret på nye, og derfor ikke fuldt udviklede, teknologier forventes store forbedringspotentialer for disse teknologier i forhold til de konkurrerende petrokemiske teknologier, som er forholdsvis fuldt udviklede. Endvidere kan potentielle fremtidige ændringer i råmaterialer til både biomaterialer og fossile materialer ændre deres indbyrdes relative miljøpræstation.

Abbreviations

1G	First generation
2G	Second generation
3G	Third generation
AGB	Above ground biomass
BGB	Below ground biomass
CCS	Carbon capture and storage
CO_2e	CO_2 equivalents
CTP	Climate tipping potential
GHG	Greenhouse gas
GTP	Global temperature potential
GWP	Global warming potential
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LUC	Land use change
ppm	Parts per million
ppt_{rc}	Parts per trillion of remaining capacity
SOC	Soil organic carbon

Synonyms

Biomaterials = Biomass based materials

Table of Contents

1 Introduction

The society of today is highly dependent on fossil oil and gas for producing fuels, chemicals and materials. However, the use of the fossil resources involves several concerns. Being fossil, it means that they are limited resources and with the increasingly high consumption since the industrialization, accessible oil reserves are going fast towards depletion and oil prices are accordingly rising. Further, the burning of fossil fuels has negative consequences for the environment and leads to climate change which has very serious consequences on a global level. For those reasons, alternative solutions to a fossil feedstock based society are increasingly yearned for, and with rising oil prices they are becoming more and more competitive. Many of the fuels, chemicals and materials today being produced from fossil resources can be alternatively produced from biological raw material (biomass), such as agricultural crops or residues. Besides biomass being a renewable resource, it can also be locally produced and can contribute to local job creation (e.g. Carus et al. 2011). For those reasons, the potential of biobased products as substitutes for fossil based ones receives increased attention, and global production is increasing. Already today a number of conventional fossil based products are also being produced based on biomass feedstock, and many more are in the pipeline. In 2003, 8-10% of the feedstock for the European chemical industry was biomass (Rothermel 2008), and the global share of chemicals being biobased was 2% in 2008 and is expected to be at least 22% by 2025 (USDA 2008), while the global share of polymers being biobased is already more than 8% today (Carus et al. 2013). Both direct substitution of some of the same fuels, chemicals and materials which are conventionally produced based on oil is possible, but also new products with different properties are being developed.

As the demand for biomaterials increase, so does the need for knowledge on the environmental performance of the biomaterials relative to their petrochemical alternatives. While the feedstock of biobased products consist of biomass, the production of the feedstock as well as other processes in the product life cycle may however have fossil fuel consumption, or in other ways contribute to GHG emissions and other environmental impacts. Life cycle assessment (LCA) is a commonly used tool for assessing environmental sustainability of products and systems, accounting for the environmental impacts during their entire lifecycle. A number of LCAs exist on biobased materials (see e.g. Weiss et al. 2012), but even though the area today has a strong focus, there is still important shortcomings in the methodology. One aspect currently being discussed is the potential climate change mitigation value of temporary carbon storage in biomaterials. But despite several attempts to account for this, no consensus has yet been reached (see e.g. Brandão et al. 2013).

Other aspects of importance for the environmental life cycle performance of biomaterials that are currently not consistently included in LCAs are land use and land use change (LULUC) related impacts, such as: Changes in biogenic carbon stocks (e.g. Cherubini et al. 2012a) and more specifically changes in soil carbon (e.g. Weiss et al. 2012), crop water consumption and erosion of soil (e.g. Weiss et al. 2012), changes in surface albedo (e.g. Cherubini et al. 2012a) and biodiversity impacts (e.g. de Baan et al. 2013; Koellner et al. 2013; Weiss et al. 2012; Michelsen 2008). Further, impacts from potential indirect land use change (ILUC), which may be substantial, is an area receiving much attention today but it is not yet operational to a point where it is included in general LCAs (e.g. Weiss et al. 2012). A consistent methodology for inclusion of all relevant environmental aspects is of course important in order to enable a holistic environmental assessment, avoiding tradeoffs between different environmental impacts.

As LCA is generally a product oriented method, addressing chosen alternatives in comparison, but not considering alternatives not included in the assessment, it does not automatically include the aspect of competition for the resources between alternative utilizations, potentially being produced from the same resource. And while biomass is a renewable feedstock, it is also finite, in terms of potential annual global production capability. Thus, there is a need to know how much biomass is potentially available on a sustainable basis, taking into account food and feed needs of a growing global population. Also, this calls for an environmental comparison of not only the biomaterials with their fossil counterparts, but also with potentially competing uses of biomass such as biofuels, to establish the most environmental effective utilization of the available resources.

1.1 Objectives

The goal of this industrial PhD project is to contribute to a more consistent methodology for LCA of biomaterials by addressing essential gaps in the existing methodology. In particular it is the goal to develop an approach for dealing with temporary carbon storage in biomaterials, in a way that illustrates the potential climate change benefit in relation to urgent short-term climatic targets. This includes consideration of the time perspective in LCA of biomaterials, in terms of impact dependency of GHG uptake and emission timing. Further, the importance of a number of the LULUC related impacts currently not consistently included in LCA will be addressed through a hypothetic case study. Those selected impacts are: changes in biogenic carbon stocks (including soil organic carbon (SOC) and timing of carbon fluxes), surface albedo and biodiversity, following establishment of a biomass production. The importance of including those aspects and the current option for doing so will be briefly discussed. Finally, it is the aim to assesses the environmental performance and perspectives of biomaterials, both relative to fossil counterparts and when considering the perspective of sustainably available biomass at a global level.

1.2 Scope

The geographical scope in this PhD project is global, as the focus is on methodology development and assessment of biomaterials at a global level.

The temporal scope is defined by the impact category considered. In most cases, environmental impacts are in principle considered for an infinite time horizon, but for global warming most assessments use a 100 year time horizon. For the approach developed in this PhD project, for inclusion of the potential climate change benefit of temporary carbon storage in relation to urgent short-term climatic targets, the temporal scope is however defined by the time until reaching a target time. This target time is the expected time of crossing a specified climatic target level. For the biomass feedstock potentials, the scope is both the current situation and future scenarios until 2050.

For the technological scope, both environmental performance of biomaterials with current technologies, and potential relative changes between competing technologies (biobased and petrochemical based) from future developments in e.g. feedstock use are discussed.

2 Definition of biomaterials

Carbon-based materials can be defined as either fossil or biobased, depending on their feedstock. Conventional petrochemical polymer (plastic) materials are based on carbon from fossil oil. This carbon has been removed from the atmosphere millions of years ago through biomass growth, and has been converted into oil and stored as such over millions of years. That carbon is not part of the natural biogeochemical carbon cycle today and thus releasing it changes this carbon balance.

Biomaterials on the other hand are produced either entirely or partly from a biomass feedstock, in the form of plants or biogenic residues/waste (Weiss et al. 2012). The plants sequester CO_2 from the atmosphere during growth and store it in the form of biogenic carbon. As this carbon has recently been sequestered from the atmosphere, re-emitting it will not change the present carbon cycle balance. The biogenic carbon is therefore often considered ‘carbon neutral’ over time[1]. This is however not the case if the biomass comes from a so-called virgin source, such as rainforest or other previously undisturbed biomes, leading to a net reduction of biogenic carbon storage.

While biomaterials cover a vast group of materials, the focus in this project is mainly on those substituting conventional petrochemical products, such as chemicals and polymers, rather than traditional biomaterials such as wood, paper and natural textiles. However, many of the aspects discussed here apply for the traditional biomaterials as well.

2.1 First, second and third generation

Biobased products are distinguished into so-called ‘generations’:

- First generation (1G): Using a feedstock based on sugar, starch, vegetable oil or animal fats
- Second generation (2G): Using lignocellulosic feedstock (e.g. agricultural residues or energy crops)

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[1] There are however some issues of timing of carbon sequestration and release which affects the ‘carbon neutrality’ aspect, as temporary release or storage of carbon may also play a role in terms of climate change, especially on short term targets (see e.g. Cherubini et al. 2012b). The issue of the potential role of temporary carbon storage in relation to climate change is addressed in Chapter 4

- Third generation (3G): A terminology often used for algae feedstock (Carus and Dammer 2013), however the term is in some cases also used to refer to a follow up on 2G, rather than to a specific feedstock (Bessou et al. 2011).

Biobased products beyond 1G are in some cases termed under one as ‘advanced’ or ‘next generation’.

2.2 Biodegradability

The terms biobased and biodegradable are often used mistakenly as synonyms. Biodegradability is a material property, which depends on the molecular structure of the material, not the feedstock (PlasticsEurope 2013). Thus, both biobased and petrochemical materials can be biodegradable, but none of them are necessarily so. What is important to understand is that once a specific material, e.g. polyethylene (PE), has been produced, its material properties are independent of its feedstock.

Further, a material being biodegradable does not inherently mean it is more sustainable. Biodegradability is a property like many others, which may or may not have a positive impact on the environmental sustainability profile of a product when considering all life cycle impacts under the relevant circumstances.

3 Temporary carbon storage

Reducing the atmospheric GHG concentration increase from anthropogenic GHG emissions through carbon removal and subsequent storage is currently discussed as an option for assisting in mitigating climate change. This can be in the form of more or less permanent storage such as carbon capture and storage (CCS), but also the potential benefit from temporary carbon storage in e.g. biomaterials is being discussed, as outlined in Chapter 3.1.

3.1 State-of-the-art

Some argue that storage of carbon for a period of time can compensate cumulative climatic impacts of CO_2 emissions, (e.g. Moura-Costa and Wilson 2000). However others argue that in a long term perspective temporary carbon storage does not give much benefit to climate change and may even have a negative climatic impact (e.g. Kirschbaum 2006; Meinshausen and Hare 2002). Others again claim, that there is a value in temporary carbon storage through its ability to reduce impacts of climate change in the short term as this can ‘buy time’ for more permanent solutions to be developed and implemented (e.g. Dornburg and Marland 2008; Fearnside 2008). A number of approaches assessing the potential climate change mitigation value of temporary carbon storage in LCA and carbon footprinting have been suggested (Brandão et al. 2013) and the handling of the issue in LCA and carbon footprinting was discussed at an expert workshop at the Joint Research

Centre of the European Commission (Brandão and Levasseur 2011). However no consensus on the issue has yet been reached (Brandão et al. 2013; Article 1: Jørgensen and Hauschild 2013; Guest et al. 2013).

3.2 Relevant timescales and the global carbon cycle

When considering the value of temporary carbon storage, the timescale on which it is assessed becomes essential. For assessing climate change impacts in LCA and carbon footprinting, global warming potential (GWP) impacts for greenhouse gases are used, often applying a 100-year time horizon, reflecting the time horizon that was adopted in the Kyoto Protocol (UNFCCC 1998). The choice of the 100-year time horizon in the Kyoto Protocol is not scientifically based, but rather reflects that this was the middle choice of the three GWP time horizons presented by the IPCC (Shine 2009). In approaches for assessing the value of temporary carbon storage, this is often interpreted as implying that impacts occurring after this time are not included (e.g. Moura-Costa 2002; Clift and Brandão 2008). Using the time horizon as accounting period like this means that when temporarily storing carbon, some of the cumulative impact that would otherwise have occurred within the accounting period will move beyond it and be considered avoided (Article 1: Jørgensen and Hauschild 2013). This is problematic as it hides long-term impacts.

A literature review of the global carbon cycle shows timescales of thousands of years for the transport of carbon from the atmosphere to pools beyond the near-surface layers of the Earth, from where it will not readily be re-emitted as a response to change in near-surface conditions, see Figure 1:

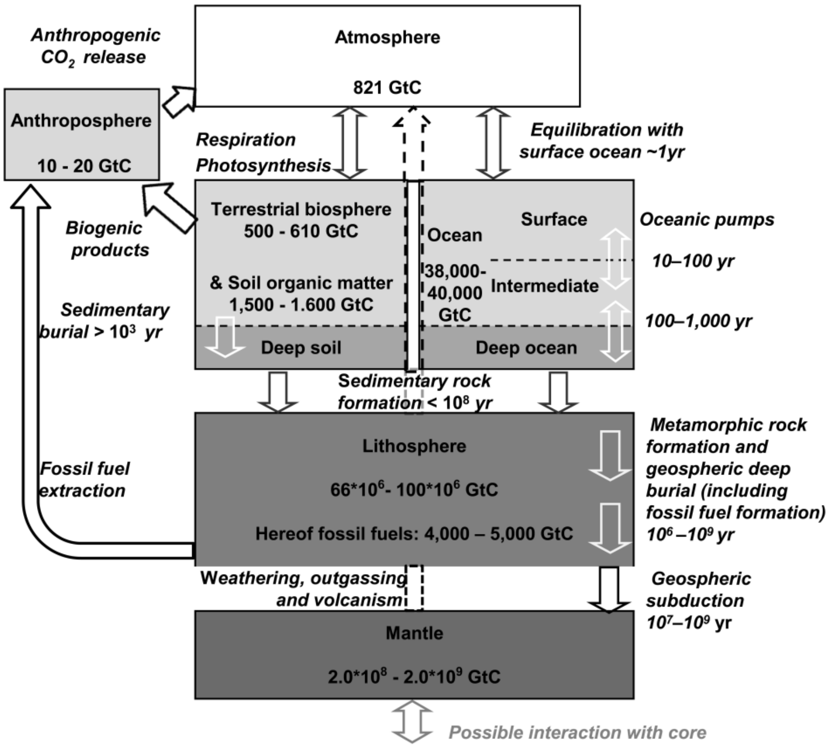

Fig. 1 (Figure from Article 1: Jørgensen and Hauschild 2013): Model of the global carbon cycle with estimates of carbon stocks, transport processes and indication of associated timescales, based on a literature study (see details and underlying assumptions in Article 1: Jørgensen and Hauschild 2013 - Online Resource 1).

Compared to this, using a 100-year accounting period does not give a meaningful picture of long-term impacts, as it causes long-term global warming impacts to be hidden by short-term storage solutions.

Assessing the dependency of the choice of accounting period on results reveals that this choice is essential for results in terms of savings in GWP, as illustrated in Table 1. Here, the approach for assessing temporary carbon storage with storage times of 2-25 years, as suggested by Clift and Brandão (2008), has been used as example for illustrating the result of cutting off climate change impacts occurring after a 100 years accounting period, compared to using other accounting periods.

Table 1 (Table from Article 1: Jørgensen and Hauschild 2013): Carbon credits for 20 years storage of 1 GtC with different accounting periods between 100 and 1000 years, using the approach for storage times of 2-25 years as suggested by Clift and Brandão (2008). Results first presented by Jørgensen and Hauschild (2010)

Accounting period, T (yr)	GWP-savings (tC)	GWP-savings (tCO_2e)
100	0.152	0.557
200	0.0740	0.271
1000	0.0162	0.0594

Due to the decisive role of the accounting period, the choice of this should be considered carefully in order to obtain results that are meaningful in reflecting the climate change mitigation value of temporary carbon storage.

If long-term climatic benefits should be ensured, it is considered to require storage of carbon for at least thousand years considering the global carbon cycle illustrated in Figure 1; thus temporary carbon storage does not have a value in terms of long-term climate change mitigation. (See further details on this in Article 1: Jørgensen and Hauschild 2013).

3.3 Tipping points and urgency

Long-term climate change implications is however not the only issue when discussing the relevance of carbon storage in mitigating climate change; it is also very important to stay below certain climatic target levels. This is due to the climate system approaching so-called tipping points, which if crossed are expected to lead to dramatic changes in the climate system that may be irreversible (Meehl et al. 2007; Hansen et al. 2008). A conceptual illustration of reversible and irreversible tipping points is shown in Figure 2:

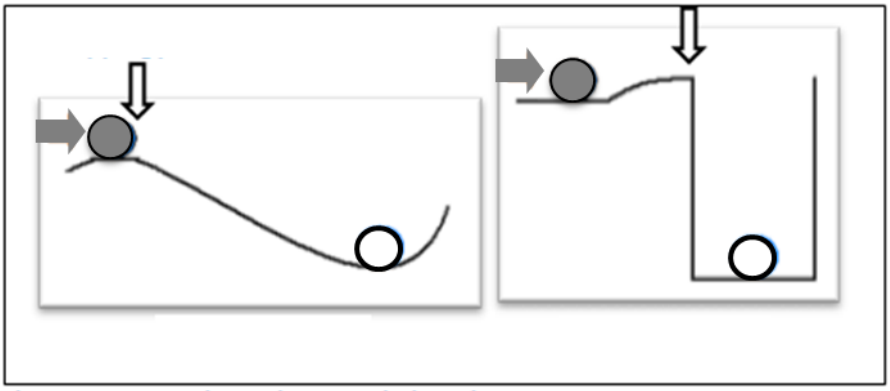

Fig. 2 Grey arrows indicate external forcing, while white arrows indicate tipping points (that are a) reversible and b irreversible) from where the external forcing no longer determines the course of event, but internal system mechanisms means a shift from one state to a new one (first state illustrated by the grey ball, second by the white ball)

To avoid passing expected climatic tipping points, mitigation of the rise in atmospheric GHG concentration is urgently required. In this perspective even short term carbon storage may be of value if it has a potential for ‘bridging’ a pathway to a low carbon future, or for ‘buying time’ by facilitating temporary solutions until more sustainable permanent solutions are available.

3.4 Development of an approach for including urgency in climate change impact assessment – the Climate Tipping Potential (CTP)

For addressing the urgency aspect the GWP approach is less fitting, as it gives equal weight to emissions irrespective of time of emission. It does not take into account the need for staying below certain climatic target levels, nor the increasing impacts of short-lived GHGs with a near-term target compared to long-term targets. The need for an alternative climate change impact assessment metric that considers climatic target levels has been increasingly recognised (e.g. Shine et al. 2007; Peters et al. 2011; Cherubini et al. 2012b).

To account for the impacts related to passing climate tipping points, without disregarding long-term impacts, it is suggested to address the value/impact of temporary carbon storage with a dual approach, including two parallel assessments; one addressing long-term perspectives and one addressing the urgency of not crossing certain climatic target levels (Article 1; Jørgensen and Hauschild 2013). In this approach, long-term impacts are still suggested to be represented by the GWP, while the impacts related to a climate tipping point are suggested to be accounted for using the Climate Tipping Potential (CTP); a new approach developed during this PhD project (Article 2: Jørgensen et al. 2014).

The idea behind the CTP approach is to express the cumulative impact of a marginal GHG emission from the emission time to the target time, with the latter being the point in time where the target level is expected to be reached, according to the selected GHG concentration development scenario. The CTP expresses how much the GHG emission takes up of the atmospheric ‘capacity’ for absorbing the impact without exceeding the target level. The remaining atmospheric capacity is thus seen as a limited ‘resource’. The conceptual idea is illustrated in Figure 3:

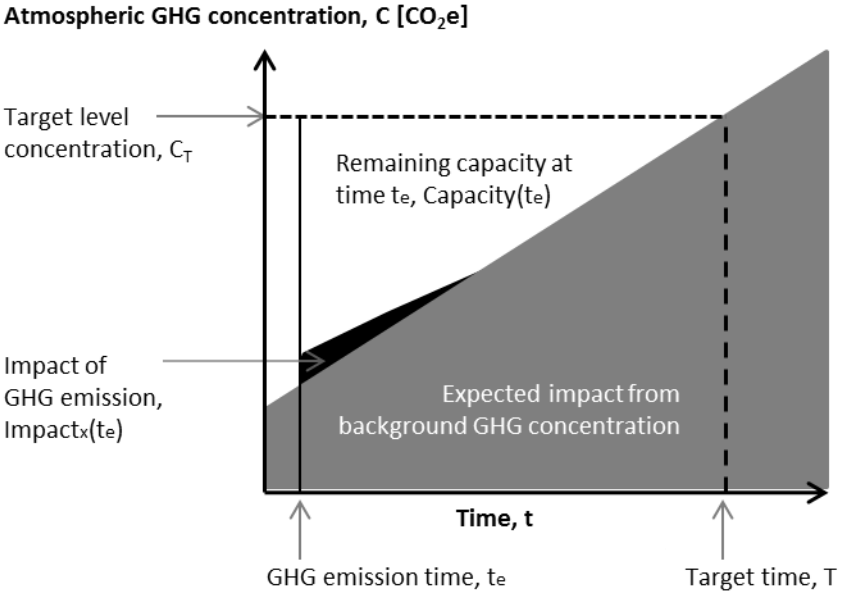

Fig. 3 (Figure from Article 2: Jørgensen et al. 2014): Conceptual illustration of the CTP approach, expressing GHG emission impacts as the fraction they take up of the remaining atmospheric capacity for receiving GHG emissions without exceeding a predefined climatic target level

As opposed to other target time approaches, such as the time-dependent global temperature potential (GTP) (Shine et al. 2007), the nature of the developed CTP approach results in increasing impacts of the assessed GHGs as the emission time approaches the target time. In this way, the results of the CTP approach reflect the rapid decrease in remaining atmospheric capacity and thus the increasing potential impact of the GHG emission.

The approach is directly applicable in LCA by using the CTP characterization factors which have been calculated for the three main anthropogenic GHGs, CO_2, CH_4 and N_2O. These have been calculated for different GHG concentration scenarios; the so-called Representative Concentration Pathway (RCP) scenarios (Meinshausen et al. 2011). CTP characterization factors for the RCP6 medium stabilization level scenario (made available by Meinshausen et al. (2011) based on background data from Fujino et al. (2006)) for selected emission years can be seen from Table 2:

Table 2 (From Article 2: Jørgensen et al. 2014): CTP characterization factors for N_2O, CH_4 and CO_2, using the RCP6 Scenario and an atmospheric target level of 450 ppm CO_2e. CTP values are given as ppt of remaining capacity, ppt_{rc}

Year of emission	N_2O [ppt_{rc} kg N_2O^{-1}]	CH_4 [ppt_{rc} kg CH_4^{-1}]	CO_2 [ppt_{rc} kg CO_2^{-1}]
2015	$1.01 \cdot 10^{0}$	$2.73 \cdot 10^{-1}$	$3.53 \cdot 10^{-3}$
2020	$1.44 \cdot 10^{0}$	$4.51 \cdot 10^{-1}$	$5.19 \cdot 10^{-3}$
2025	$2.50 \cdot 10^{0}$	$9.19 \cdot 10^{-1}$	$9.43 \cdot 10^{-3}$
2030	$8.47 \cdot 10^{0}$	$3.70 \cdot 10^{0}$	$3.53 \cdot 10^{-2}$
2031	$1.38 \cdot 10^{1}$	$6.25 \cdot 10^{0}$	$6.01 \cdot 10^{-2}$

See details on the approach in Article 2: Jørgensen et al. (2014), and CTP characterization factors for all emission years from present until the target time, for all four RCP Scenarios, in the appertaining Online Resource 1.

3.5 Inclusion of potential temporary carbon storage value in LCA

The nature of the CTP approach means that it has potential for estimating the climate change mitigation value of temporary carbon storage, in terms of helping avoiding crossing climatic target levels. However, it needs to be adapted to be able to distinguish the value of permanent carbon storage from that of temporary carbon storage.

In order to do this, a storage period defined as having full benefit equal to that of permanent storage, τ, is defined. Here a value of $\tau = 50$ years is chosen, from the argumentation of the urgency of buying time, in order to avoid crossing the climatic target level. For shorter storage times of a minimum of 2 years, a gradual value for all temporary carbon storages which ends after T, has been established as the fraction-wise value in terms of storage period (e.g. 2 years storage having 1/25 the value of 50 years storage). Sequestration of CO_2 with following storage is modelled as negative emissions. This is summarised in Equation (1) from Article 3: Jørgensen et al. (2015):

If $t_{st} < T \le t_e$:

$$CTP_{\mathrm{TCS},T}(t_{st},t_e) = \frac{n}{\tau}\left[\frac{\left(\dfrac{\int_{t=t_e}^{t=T} A_{CO2}[a_0+\sum_i a_i \exp(-t'/\alpha_i)]dt'}{A_{CO2,ppm}}\right)}{\int_{t=t_e}^{t=T}(C_T-C_t)dt} - \frac{\left(\dfrac{\int_{t=t_{st}}^{t=T} A_{CO2}[a_0+\sum_i a_i \exp(-t'/\alpha_i)]dt'}{A_{CO2,ppm}}\right)}{\int_{t=t_{st}}^{t=T}(C_T-C_t)dt}\right] \tag{1}$$

Where $CTP_{TCS,T}(t_{st},t_e)$ is the climate tipping potential of temporary carbon storage from time of sequestration and following storage, t_{st}, until emission time t_e, and a target time T, n is the length of the storage period from 1 to τ, with all periods above τ having a value equal to that of a period of τ, A_{CO2} is the specific radiative forcing of CO_2 *per kg* in the atmosphere and $A_{CO2,ppm}$ is the specific radiative forcing of CO_2 *per ppm*, a and α are coefficients and time constants for the removal processes that are active in the IPCC decay function for CO_2 in the atmosphere, according to the revised Bern carbon cycle model (Forster et al. 2007): $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\alpha_1 = 172.9$ years, $\alpha_2 = 18.51$ years, $\alpha_3 = 1.186$ years, C_T is the target level concentration of atmospheric GHG, occurring at the target time T, and C_t is the concentration of atmospheric GHG at time t of the assumed GHG concentration scenario.

In the case where $t_{st} < T > t_e$, Equation (2) applies (Article 3: Jørgensen et al. 2015):

$$CTP_{TCS,T}(t_{st},t_e) = \frac{\left(\dfrac{\int_{t=t_e}^{t=T} A_{CO2}[a_0 + \sum_i a_i \exp(-t'/\alpha_i)]dt'}{A_{CO2,ppm}} \right)}{\int_{t=t_e}^{t=T} (C_T - C_t)dt} - \frac{\left(\dfrac{\int_{t=t_{st}}^{t=T} A_{CO2}[a_0 + \sum_i a_i \exp(-t'/\alpha_i)]dt'}{A_{CO2,ppm}} \right)}{\int_{t=t_{st}}^{t=T} (C_T - C_t)dt} \quad (2)$$

Using Equation (1) and (2), CTP characterization factors for temporary carbon storage for all storage and emission times from present until the target time can be calculated. As can be seen from Figure 4, temporary carbon storage gives a CTP saving if the carbon is stored beyond the target time, but increases CTP impacts if carbon is released again before the target time.

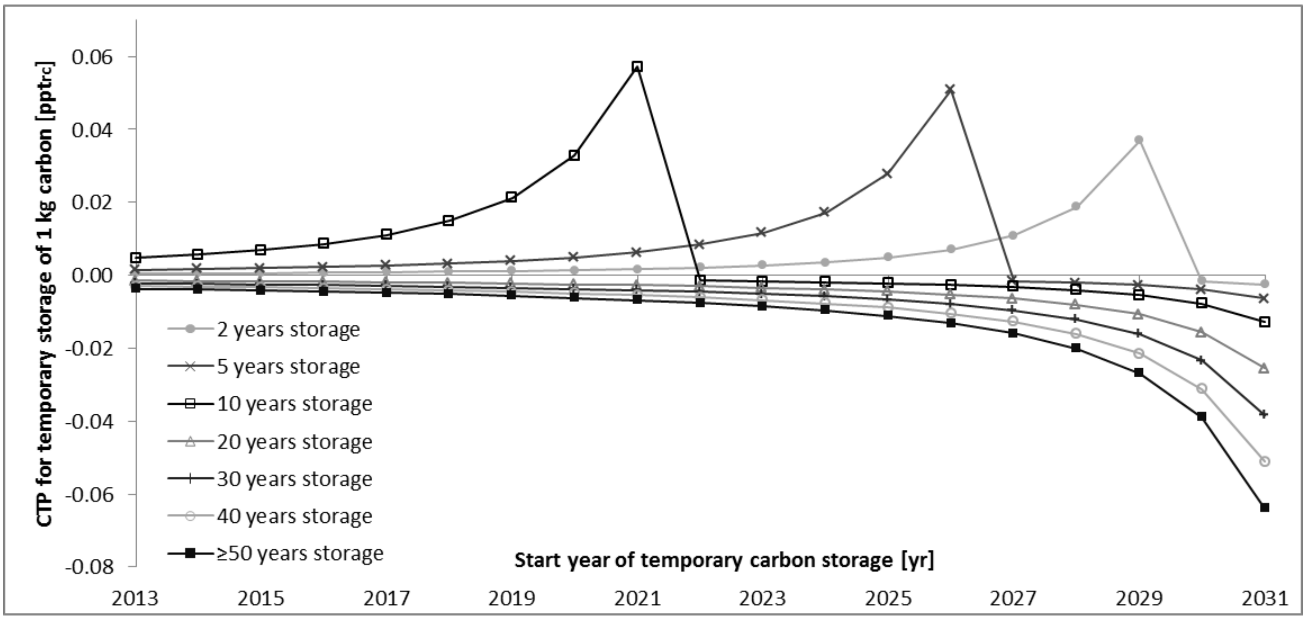

Fig. 4 (Figure from Article 3: Jørgensen et al. 2015): CTP for temporary carbon storage, with different years of carbon sequestration before T, and for different storage durations, assuming Scenario RCP6. CTP is measured in ppt of the remaining atmospheric capacity (ppt_{rc}) for taking up GHGs without exceeding the target level. Negative values illustrate mitigation potential

Figure 4 shows the development in CTP characterization factors as function of year of carbon sequestration as well as storage durations for the RCP6 Scenario. A similar illustration of CTP characterization factors for the RCP3PD Scenario (a mitigation scenario with a peaking radiative forcing in year 2044, followed by a decline) can be seen from Article 3: Jørgensen et al. (2015), along with further discussion of the results. The RCP3PD Scenario is made available by Meinshausen et al. (2011), based on background data from van Vuuren et al. (2007). CTP characterization factors for all storage durations for different sequestration times are given for both the RCP6 and the RCP3PD Scenario in Article 3: Jørgensen et al. (2015), Online Resource 1, which enables direct inclusion in LCA.

Introducing the CTP approach in the environmental impact assessment of biomaterials enables that the potential benefit from temporary carbon storage in biomaterials, in terms of avoiding or postponing a dangerous climatic target level, can be included in their environmental profile. This also entails that the different CTP potentials from different biomaterials, and the use of different feedstock, processes etc. in the life cycle, can be distinguished. The potential mitigation value of the temporary carbon storage is highly dependent on the timing of sequestration and re-emission of carbon (in the form of atmospheric $CO_{2)}$ relative to the target time. Re-emission before the target time even increases the CTP impact rather than mitigating it, as illustrated in Figure 4.

The total CTP impact of a biomaterial is made up of the sum of both the CTP impact/saving of the temporary carbon storage and of the GHG emissions during the product life cycle. An example of this can be seen in Figure 5, for three different types of biobased polyethylene (PE) products with different lifetimes and thus carbon storage durations, from three different biomass feedstocks, and with carbon sequestration occurring in three different years. Modelling of GHG emissions for PE production from the three types of biomass is based on background data from Bos et al. (2012), which describes current agricultural practice. Thus in the case of miscanthus and sugar cane, GHG savings from energy production from co-products is included (see more details on calculations in Article 3: Jørgensen et al. 2015).

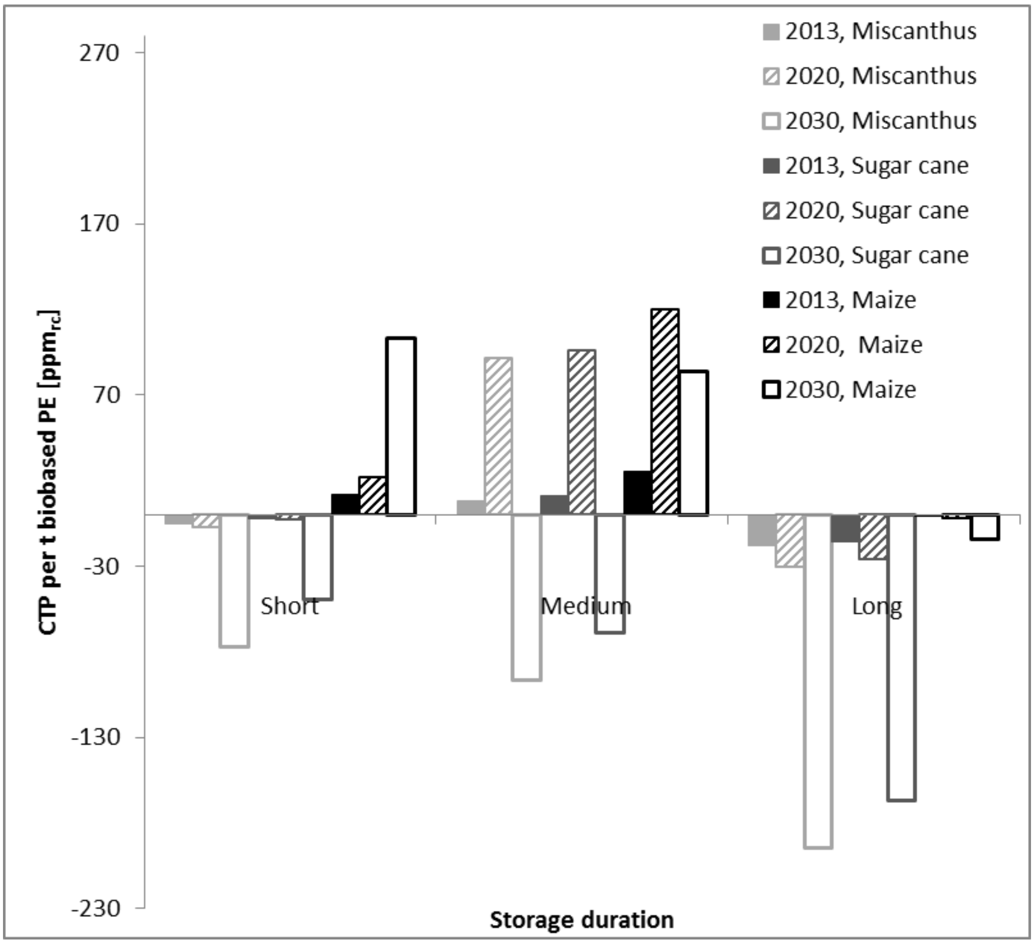

Fig. 5 (Figure from Article 3: Jørgensen et al. 2015): CTP of temporary carbon storage in one t biobased PE products, with different storage durations (short: 2 years, medium: 10 years, long: above 50 years), for different years of carbon sequestration, including life cycle GHG impacts, for three different feedstock crops, using the RCP6 Scenario

While results for only the temporary carbon storage are rather homogenous as illustrated in Figure 4, including the life cycle GHG impacts makes the picture look a bit more complex, as the two types of impacts vary differently with storage duration, timing of sequestration and feedstock type. Savings in GHG emissions gives negative CTP values (savings), while GHG emissions give positive values, but the magnitude depends on the timing of the emissions relative to the target time. A biobased product has a negative CTP value if it has a net mitigation of climate tipping potential during its entire life cycle, e.g. when the sum of CTP values from the temporary carbon storage and the CTP impacts of the product over the rest of its life cycle is negative. (See similar results for the RCP3PD Scenario and more discussion of results in Article 3: Jørgensen et al. 2015).

3.6 The climate change mitigation potential of temporary carbon storage in biomaterials

The carbon storage inherent in biomaterials has a potential climate change mitigation value - both in terms of temporary and permanent carbon storage. The magnitude of the potential climate change mitigation value of temporary carbon storage is addressed here, while the aspect of permanent carbon storage is dealt with in Chapter 4.

As the climate change mitigation value of temporary carbon storage lies in temporarily removing CO_2 from the atmosphere, it should be assessed relative to avoiding or postponing the crossing of short-term climatic target levels. Here, a climatic target level of 450 ppm CO_2e atmospheric GHG concentration is chosen, as discussed in Article 2 (Jørgensen et al. 2014). The potential value of the temporary carbon storage further depends on the expected development in atmospheric GHG concentrations.

Here, the RCP3PD and the RCP6 scenarios for GHG concentration development have been used. The trends of the two scenarios mean that storage of enough carbon for a sufficiently long period of time has bridging potential by contributing to avoid the crossing of the 450 ppm target level assuming the RCP3PD scenario, and the potential to buy time by contributing to postpone the crossing of the target level assuming the RCP6 scenario. This potential value of temporary carbon storage in biomaterials can be estimated, comparing the potentially stored amount to the estimated amount of carbon emission that must be avoided.

Using the RCP3PD Scenario, the predicted time of exceeding the target level, which must be bridged, is 24 years, as illustrated in Figure 6 a).

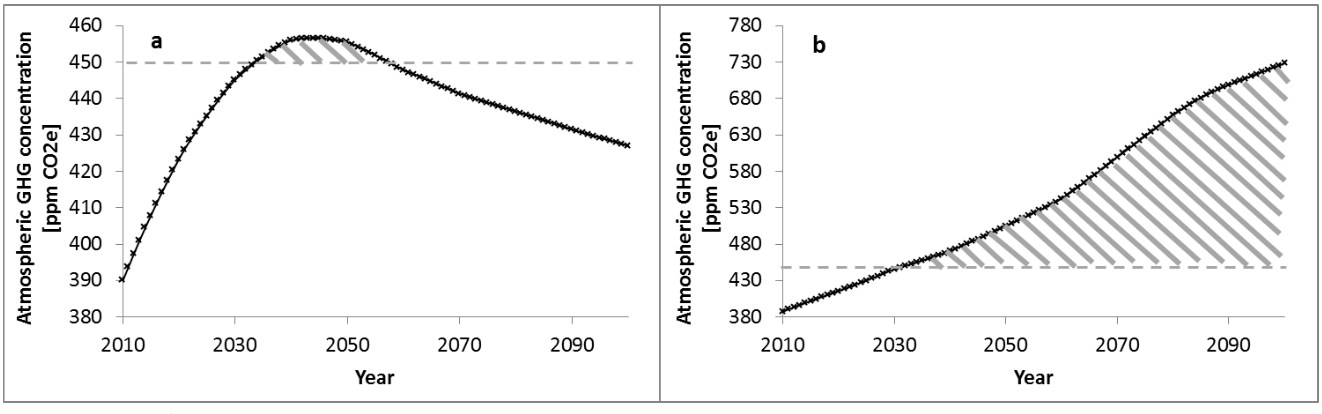

Fig. 6 (Figure from Article 3: Jørgensen et al. 2015): a) the peak and decline scenario (RCP3PD) (Meinshausen et al. (2011) and van Vuuren et al. (2007)) and b) the continuous increase scenario (RCP6) (Meinshausen et al. (2011) and Fujino et al. (2006)), with illustration of expected excess atmospheric GHG concentrations (grey hatched area) above a 450 ppm CO_2e target level (grey punctured line)

Considering this, only biopolymers used in building and construction, which are expected to have longer average lifetimes than 24 years, are considered here. A rough estimate of the potential climate change mitigation value of these biopolymers, in terms of avoiding the 450 ppm CO_2e target level, is estimated by assuming full substitution of the global production of polymers for building and construction with biopolymers. Covering the global demand for building and construction polymers with biopolymers is here only considered from the year the RCP3PD Scenario predicts that the target level will otherwise be crossed, which is 20 years from now.

The carbon storage in long-lived biopolymers as described here, produced from the time the target level would otherwise be expected to be crossed, could account for at least 26% of the carbon that must be avoided emitted each year (as CO_2) from 2034 until 2057, assuming the RCP3PD Scenario (Article 3: Jørgensen et al. (2015)). In many years, it could even contribute with a saving larger than the needed. Assuming the RCP6 Scenario, the potential value of carbon storage in the long-lived biopolymers is expressed in terms of contribution to avoiding the target level for the first 50 years after it is predicted to be crossed, as no bridging is possible due to the continuous increase in atmospheric GHG concentration (as can be seen in Figure 6 b). The potential of the long-lived biopolymers for doing so in this case is 10-28% each year, except for the first year, where it is 90%, as the target level is only expected to be slightly exceeded that year (Article 3: Jørgensen et al. (2015)). Details on calculations can be seen from Article 3: Jørgensen et al. (2015).

4 Carbon stock changes

For the carbon stock in the biosphere, the development has in the last many years been a drastic decrease, with large amounts of virgin forest being cleared, e.g. for using the timber or opening the land for agricultural production. Further, the fraction of carbon stored in the lithosphere which is in the form of fossil resources; oil, coal and gas, has also been heavily extracted and consumed since the industrialization. Both developments have led to decrease in formerly permanent stocks of carbon (on reasonable timescales).

A fraction of the carbon from the biosphere and fossil carbon from the lithosphere is stored in the anthroposphere in the form of products, e.g based on wood or plastic. However the largest part by far has been released to the atmosphere, leading to a drastic increase in the carbon stock there, with associated environmental impacts as a consequence, here among climate change. When the carbon stock in the atmosphere, in the form of CO_2, is increased, the increased CO_2 concentration induces a concentration gradient pressure between the CO_2 concentration in the atmosphere and the ocean, leading to a net uptake of CO_2 by the ocean. While this mechanism removes large parts of the atmospheric CO_2, a substantial fraction stays in the atmosphere for thousands of years (Archer et al. 1997). Further, the increase of carbon in the ocean leads to increased acidification which may have large implications for the marine ecosystem. The described current carbon stock change trends can be seen in Figure 7.

However, if considering the biobased society vision, of replacing fossil fuel feedstock of today's society with a biobased one, this would also impact the carbon stocks trends. While single product carbon storage may be temporary, the resulting stock changes are usually more long-term, or even permanent.

The biobased society vision would lead to a scenario where, for one thing, carbon flows from the lithosphere in the form of fossil fuels would be reduced (and in case of full substitution, completely avoided). Secondly, if substituting the current fossil-based material production with a biobased one, more biomass is needed. If this biomass is additionally produced, not supplied by consuming existing biomass stocks (e.g. current crops, forests, etc., as well as not leading to lower levels of biogenic carbon stocks in the area) this leads to an increase in the carbon stock of the biosphere. Supplying the additional biomass can be done in various ways, e.g. using surplus agricultural land, increasing yields of existing agricultural production, or using energy crops on degraded land not suitable for normal agricultural production. Third, increasing the carbon stock in the biosphere through additional biomass production means withdrawing carbon (in the form of CO_2) from the atmosphere, thus yielding a climate change saving. However, due to the internal mechanisms of the global carbon cycle, part of this saving may be compensated by some degree of release of CO_2 from the ocean to the atmosphere, as the balance of the CO_2 exchange between the two compartments depends on the air–sea CO_2 concentration gradient (e.g. Archer and Brovkin 2008).

The transition from petrochemical to biobased society would not lead to a change in anthropogenic carbon stocks, assuming substitution of products with similar carbon properties. However, at curent the global production of polymers keeps increasing, which increases the carbon stock in polymers in the anthroposphere. And with a growing global population and expanding consumption patterns, this points to a continuous increase in polymer production for many years. As long as this trend continues, it means that each year's stock increase in the anthroposphere and biosphere, and the associated changes in the other carbon stocks, can be considered permanent, as they will not be reversed by a decrease in production the following years. The induced trends in carbon stock changes due to a biobased society scenario can also be seen in Figure 7.

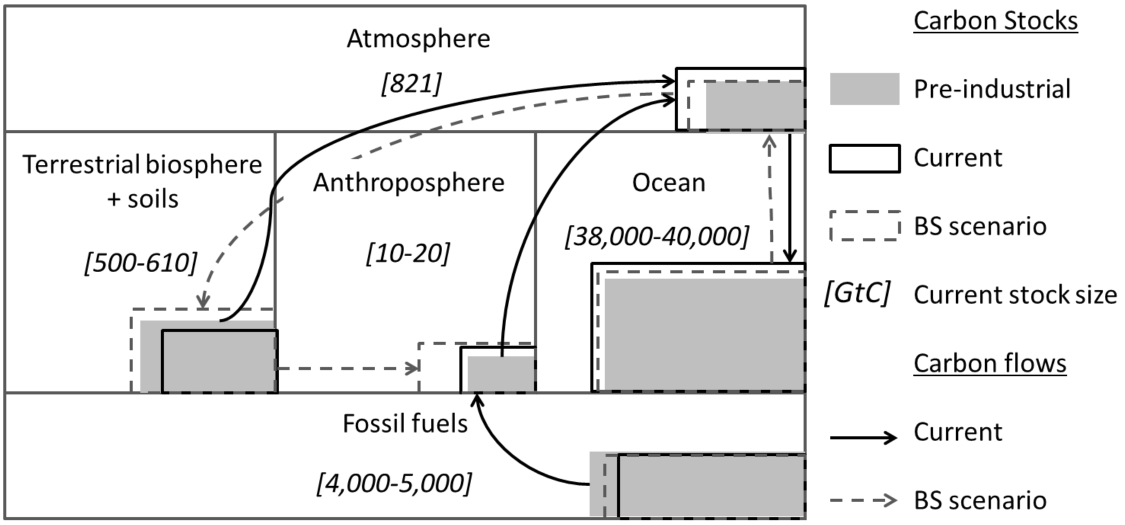

Fig. 7 Conceptual illustration of trends in changes for relevant carbon stocks of the global carbon cycle in terms of exchanges affected by anthropogenic behavior. From pre-industrial to current situation, as well as for the potential biobased society (BS) scenario development in stocks due to main net flows. Current stock sizes are based on the model of the global carbon cycle in Figure 1, based on a range of literature values (see Article 1: Jørgensen and Hauschild 2013, Online Resource 1)

5 LULUC impacts

LULUC for producing biomass for biomaterials can impact a number of environmental aspects in different ways, of which not all are usually considered in LCA. The current status in terms of inclusion in LCA of some of these main aspects, and their potential importance for LCA results, are discussed in this chapter, based on a theoretic case study conducted during the PhD project (details on the theoretic case study, along with background data and assumptions, can be seen in Article 4: Jørgensen et al. (2014)).

5.1 Albedo

Albedo is a measure of surface reflectivity, in terms of the fraction of incoming solar radiation which is reflected by a surface. Albedo values differ a lot depending on the type of land cover; e.g. surfaces covered in snow and ice have much larger albedo than darker surfaces, for instance areas covered with forest (Bright et al. 2012a; Cherubini et al 2012a). As higher reflection of solar radiation means that less heat is absorbed, the effect of increased albedo is cooling, whereas decreased albedo of a surface leads to warming. Land use change (LUC) can lead to important changes in albedo of an area, and can thus be of major importance in relation to global warming. For instance, while deforestation has a warming effect through the biogenic CO_2 release from standing biomass and SOC, the cooling effect from increased albedo can in some cases be even larger, leading to a net cooling effect (Randerson et al. 2006; Bala et al. 2007; Betts 2007; Davin et al. 2007; Cherubini et al. 2012a; O'Halloran et al. 2012). Other biogeophysical effects exist, but on a global scale the albedo effect is the dominating direct climate forcing of these, especially in locations seasonally covered in snow (Claussen et al. 2001; Randerson et al. 2006; Bala et al. 2007).

As it is recognized that albedo changes can play an important role in terms of climate impacts it is increasingly included in climate impact assessments of bioenergy systems (Georgescu et al. 2009; Loarie et al. 2011; Georgescu et al. 2011; Anderson-Teixeira et al. 2012; Bright et al. 2012a; Bright et al. 2012b; Cherubini et al. 2012a). However, in LCAs of such systems, albedo is not included on a routine basis. Through a theoretic case study (Article 4: Jørgensen et al. 2014) the potentially important role of albedo changes in terms of climate change impacts from a LUC is illustrated, and the necessity of including this aspect on a routine basis in LCA of product systems where LUC and/or ILUC occur is thus supported.

A procedure for including albedo in LCA already exist, as the climate forcing from change in albedo from a LUC can be compared to that of GHG emissions in terms of radiative forcing (RF) (Betts 2011; Bright et al. 2012a; Cherubini et al. 2012a). However, different types of climate forcings can have different climate efficacies which determine the climate response per unit of the forcing, such as change in global mean temperature. In order to compare two types of climate forcings in terms of effect on global mean temperature, the effective forcing can be used, which is the product of the instantaneous radiative forcing and the climate efficacy of the climate forcing. The radiative forcing and effective forcing of a change in albedo can be computed and included in an LCA according to Cherubini et al. (2012a). The albedo values of different land cover types at different geographical locations can be obtained using historic satellite data. Albedo values vary with the seasons, especially in areas seasonally covered in snow. In order to reduce uncertainty related to annual variability in climate and phenology, average monthly data for a representative period of years can be used.

While the inclusion of albedo impacts on climate change from a LUC may be somewhat time-consuming, it is both possible and crucial to include it in climate change impact assessment in LCAs of products and systems including LUC. However, the availability of relevant data of course requires that there has been a land use in the area similar to that which is being assessed, for a sufficient period of time.

5.2 Biogenic carbon fluxes

Biogenic carbon stocks of an area consist of above ground biomass (AGB) of the plants such as stem, branches and leaves, below ground biomass (BGB) of the plants, which means roots above a certain size, and soil organic carbon (SOC) in both organic and mineral soils including roots too fine to be included in BGB. Biogenic carbon stock depends on both crop type, management and previous land use, and are site-specific as they depend on local conditions such as climate (Cowie et al. 2006; Anderson-Teixeira et al. 2009; Djomo et al. 2011; Cherubini et al. 2012a).

While AGB of a former land use will be replaced by that of the new land use, literature shows that approximately 20-40% of SOC from uncultivated land is typically lost during conversion to cultivation, and most within the first few years (Davidson and Ackerman 1993). Over time, new land use can either result in decrease or increase of SOC content, depending highly on SOC content of the former land use and crop and management type of the new land use (Cowie et al. 2006). Likewise, the magnitude of net loss or gain of total biogenic carbon stocks (i.e. biogenic carbon flux) of an area over a period of time following a LUC depends on the magnitude and pace of new carbon sequestration compared to that lost from the former land use. Thus planting crop with high potential for biogenic carbon sequestration on soil with previous low biogenic carbon content, e.g. degraded land, can lead to increased biogenic carbon stocks in the area, whereas clearing carbon rich forest for planting crops will likely have the opposite effect (See an example on this in Article 4: Jørgensen et al. 2014). Results of biogenic carbon stock changes are also highly dependent on the time period of the assessment.

SOC stocks can also be affected without changing the crop type, as in the case of removing agricultural biomass residues from the field, e.g. as feedstock for biobased products or energy production (e.g. Anderson-Teixeira et al. 2009; Don et al. 2012). While increased biomass residue removal is likely to decrease SOC content, this depends largely on the type and fraction of removal and the alternative fate of the carbon in the residues if left on the land. E.g. root and leaf litter constitutes the major input to SOC in many biomass production systems and leaving this behind diminishes the SOC decrease. Further, a large part of the coarse biomass residues are expected to decay at the surface if not removed, meaning atmospheric emission of the carbon rather than soil carbon replenishment. Both aspects limit impacts of residue removal from biomass systems (Cowie et al. 2006).

As biogenic carbon fluxes from LUCs are to a high degree case-specific, available data is required for the specific case, or at least for a similar situation in terms of location, crop and soil type, previous land use etc. This is a main challenge of including this aspect at a site-specific level on a routine basis in LCA.

5.3 Biodiversity

Biodiversity change is a widely recognized environmental issue following a LUC due, e.g. to biobased feedstock production. Biodiversity is a measure of the variability between and within living species and ecosystems (UNEP 1992), though specific definitions differ. The loss of biodiversity has been identified as a key environmental concern (e.g. Diaz and Cabido 2001) and habitat loss and (local) species extinction due to a changed land use is expected to be the main driver of biodiversity changes in terrestrial ecosystems (Sala et al. 2000). Other important aspects in terms of biodiversity changes are increased atmospheric carbon dioxide concentrations and climate change, nitrogen deposition and introduction of invasive species (Sala et al. 2000). As for other impacts following a LUC biodiversity impacts depend on the state of the former land use, while the type of biomass grown after the conversion also plays a role, and in some cases a LUC can even lead to a positive biodiversity development in an area (Campbell and Doswald 2009).

However, no consensus on how to handle the implementation of biodiversity in LCA has yet been achieved and approaches on the aspect are still on a rather preliminary level with substantial shortcomings (e.g. de Baan et al. 2013; Koellner et al. 2013; Michelsen 2008). Generally, existing approaches for assessing LUC impacts on biodiversity can be divided into a group focusing on changes in species composition and one focusing on structural changes, key factors and change in habitats. A severe challenge for all the approaches is the lack global available data (de Baan et al. 2013). Two of the most advanced approaches, which stand out in terms of geographical validity and spatial resolution, are the ones presented by de Baan et al. (2013), and Michelsen (2008) (which has been made globally applicable by Coelho and Michelsen (2013)). The method presented by the Baan et al. (2013) focuses on changes in species diversity, while the method presented by Michelsen (2008) focuses on rareness as well as structures necessary for biodiversity. In common for both methods are that they consider biodiversity impacts of a land use compared to the natural state of that area before human interference. Thus, using those methods to assess the difference in biodiversity in an area due to a new land use, the impact on biodiversity of the use of the land before the assessed LUC is not considered. The reason for this is that the use of a land area is seen as a delay in getting back to its natural state (de Baan et al. 2013). However, not considering the former land use e.g. means that turning a virgin forest into a crop production is considered to have the same impact on biodiversity as using an already biodiversity degraded area, which was once virgin forest. This does not seem a fair reflection of reality.

Even if assuming that the degraded land would get back to its natural state if left alone, this will take time, and thus there will as minimum be a time lag before this area reaches the same biodiversity level as a similar land area which has stayed at the natural state. Further, in many cases the surrounding area of a land degraded from the natural state will have changed too, species may have been locally extinct, and conditions may not facilitate a turn back to the natural state. This advocates for the assessment method reflecting the difference in biodiversity impact from using virgin land and already degraded land that once was similar virgin land.

When the goal is to assess the difference in biodiversity impact following a LUC from one human influenced land use to another, an elaboration of both methods to reflect this is thus suggested, by comparing the biodiversity level of the former land use and the new land use, rather than comparing the new land use to a reference state of natural biodiversity in the area, before human influence. (In fact, this is the same as considering the different biodiversity impacts of two competing potential land uses for implementation on a certain land, using the two methods). Application of this suggested elaboration on a hypothetic case study can be seen in Article 4: Jørgensen et al. (2014) along with further discussion on impacts of this on results etc.

One could argue, that in a case where the new land use in the assessed area would lead to ILUC, that could potentially mean that a virgin land area might be converted somewhere else, by implementation of the former land use of the assessed area. This would be the case if virgin land is the marginal available land assumed to be used for the production of what was previously produced on the area of the LUC assessed (see more on the definition and modelling of marginal land use in Kløverpris (2010)). However, if a LUC leads to an ILUC, a correct way to deal with that would be to assess the biodiversity impact of the latter separately, along with the other environmental impacts of the ILUC, taking into account where it is expected to take place and thus the geographical specific impacts. Whether a LUC will lead to ILUC somewhere else depends on whether the former land use is still needed. E.g. in a case of introducing a LUC on a land formerly used to produce a crop, this crop will need to be produced somewhere else, to fulfil the same demand (e.g. Kløverpris 2010). However, in the case where the use of the former produced crop is substituted by the new crop (e.g. 1G crops as feedstock for biofuels being substituted by 2G crops for the same purpose) this will not lead to ILUC if the end product yield produced per area of the new crop production is the same as that of the former crop production. (If the new land use has a higher yield per area than the former, the result in such a case will on the contrary be land savings.)

As both the method by de Baan et al (2013) and the one by Michelsen (2008) include substantial uncertainty, a comparison of the results of both methods has been performed on a case study of biodiversity impacts from a hypothetic change in land use, in order to determine whether they support the same conclusions. This comparison shows that the original methods give potentially very different results, not only between methods, but also comparing results within each method to either neighboring ecoregion (for the Michelsen (2008) method) or average global data (for the de Baan et al. (2013) method). This is assumed to be mainly due to lack of geographical specific data. However, when using the suggested elaboration of both methods, a qualitative agreement can be seen, as all methods point to the same preferred change in land in terms of biodiversity impacts, even though quantitative results still vary greatly (see more results and discussion on this in Article 4: Jørgensen et al. (2014)).

The lack of consensus on assessment method and the lack of geographical specific data are main obstacles for obtaining quantitative and reliable results of biodiversity impacts in LCA. However, due to the importance of this aspect, obtaining qualitative or rough quantitative results of best available approaches is considered better than disregarding biodiversity impacts. Comparison of results from several methods can be used to address the uncertainty issue. It is here recommended to use the current biodiversity level as reference state for the assessment, rather than the natural state, for including the biodiversity impact of the previous land use.

5.4 Potential tradeoffs

Effective forcing offsetting from surface albedo increases when dense vegetation covered areas such as forests are replaced with crops being cut down annually (especially in seasonally snow covered areas). However, this type of changed land use can at the same time substantially decrease biodiversity in the area. This tradeoff effect is illustrated in Figure 8.

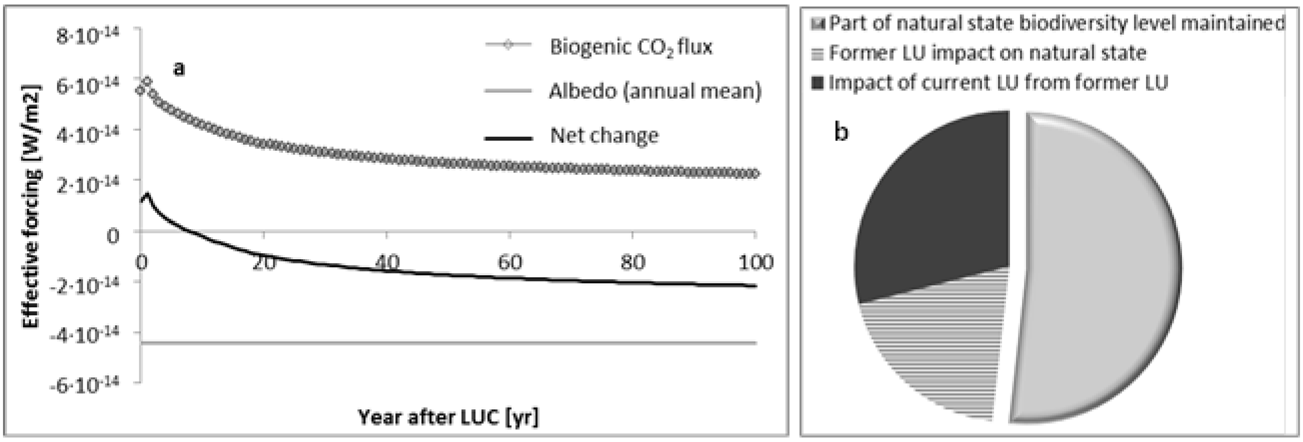

Fig. 8 (Selected parts of result figures from Article 4: Jørgensen et al. 2014): Change in a) effective forcing for 100 years from the time of the LUC in the specified geographical area for both biogenic CO_2 flux, albedo change and the net change of both effects, and b) for the induced biodiversity impact, in the case of producing miscanthus on a former forest area

The results shown in Figure 8 clearly illustrate a potential tradeoff between effective forcing and biodiversity impacts following a LUC. The importance of these impacts, as well as the potential tradeoffs between them, supports the need for inclusion of the best possible assessment of these impacts in standard LCAs of biomaterials, despite the challenges currently existing for assessing some of them. This is needed in order to get a realistic picture of the overall environmental impacts from a biomass feedstock crop establishment, and thus of downstream products of the biomass feedstock.

6 Available biomass potential and competition issues

A central sustainability issue of biomaterials is the feedstock; biomass. LCA in various ways addresses the sustainability aspects of the biomass production and associated LUCs (with the limitations described in Chapter 1). Another crucial aspect is however the availability of a sufficient amount of biomass at a global level, both now and in the future. This biomass should be sustainable, in the sense that it neither leads to deforestation or similar depletion of natural habitats, nor takes up the land needed for feeding the growing global population.

6.1 Biomass potential and demands for biomaterials and bioenergy

Available biomass potentials and demands are considered at a global scale, as they are typically not constrained within national borders, but traded across, due to global market mechanisms.

A global predicted available biomass potential range for today as well as year 2030 and 2050 is compared to estimates of demands for energy (including fuels) and organic chemicals (including polymers) in the same years in Figure 9. The figure is based on a review of literature data and estimates, and to some extend conversion and extrapolation of those (see details and assumptions in Appendix 1).

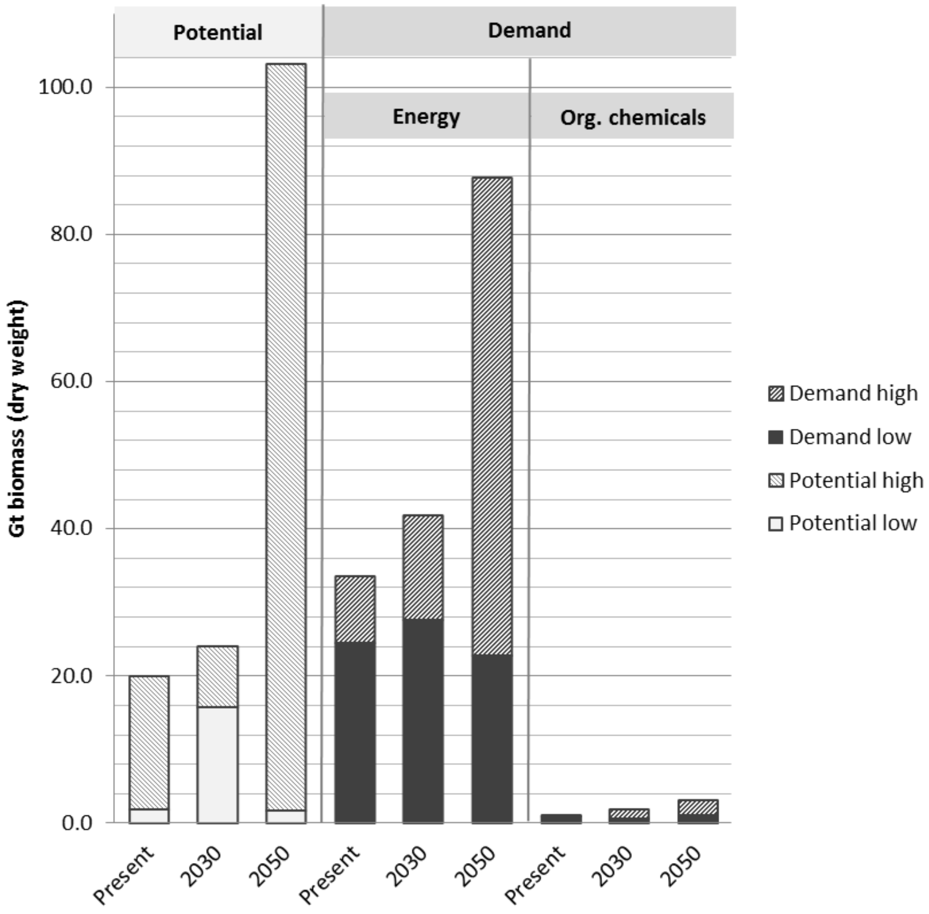

Fig. 9: Estimated potentials for global biomass feedstock sustainably available[2] for substituting fossil fuel demands from energy[3] and organic chemical production, from present until 2050

What can be seen from Figure 9 is that there are large variations in the estimates of both potentials and demands. A part of this variation is due to the conversion from energy units (generally used in original references) to mass (dry weight), which has been done using an energy density range of biomass of 15-19 GJ/ton (see background in Appendix 1).

Further, the estimated potentially available amount of biomass differs significantly between references, partly due to varying assumptions on what is economically feasible and environmentally sustainable. Some key reasons for large variations between different literature estimates are:

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[2] The biomass potentials do not include possible ‘blue biomass’ potential (biomass from the ocean, e.g. algae)

[3] Estimate ranges exclude energy demand covered by nuclear power, as well as hydro power and other renewable energy sources other than biomass and waste (to the extent that the latter have been separable in the reference), meaning that it gives the global biomass demand for substituting fossil fuel energy production (see more details in Appendix 1)

- Estimated future biomass/land demand for food, feed etc. vary with different development assumptions
- Some estimates are given as the technical potential, which in itself can vary significantly due to different future assumptions, whereas other address a potential which also includes practical aspects such as collection loss and competing use of the biomass
- The issue of the biomass production being sustainable has a varying focus in the different studies, and is addressed differently, e.g.:
    - Some studies include assumptions of a high degree of energy crops in the future, either replacing existing crops, or being grown on additional land
    - Assumptions for additionally available land for biomass production on a sustainable level varies a lot
    - A potential for available biomass from residues and waste is not included in all studies, while others only include this potential
    - Inclusion and handling of the aspect of leaving biomass in the fields for soil enrichment and replenishment of soil carbon content differs between studies

The estimates of the future demand for energy and organic chemicals also vary a lot, primarily depending on the future development scenario used. The given estimates for future energy demand thus covers different scenarios form high economic growth scenarios to environmentally oriented development scenarios, which has high impact for the estimated future demand.

As future demands and potentials of biomass availability to a large degree depend on various development scenarios, this explains the increasing variation in estimates with time into the future which can be seen from Figure 9.

Despite the large variations in biomass potentials and demands, some general conclusions can still be drawn based on the results from Figure 9:

- On a global scale, most estimates support that there are sufficient amounts of biomass sustainably available to cover the global need for polymers and other organic chemicals, both today and towards 2050.
- The available biomass level today and towards 2050 is however not expected to be sufficient to cover the entire fossil fuel energy demand as well, (except for the most optimistic estimates in 2050)
- As the need for biomass in order to substitute the entire fossil fuel demand for energy and organic chemicals thus seems to be greater than the amount available at a sustainable level, there will be a competition issue, meaning that a prioritization of the biomass use will be necessary

The estimates above address the potential for total substitution of fossil fuel use for energy and organic chemicals (including polymers) with biomass feedstock, in order to give an overview of the potential options and limitations of a future biobased society. In reality, substitution of fossil fuel use with biomass feedstock will happen gradually, and will depend on e.g. economic and technological development.

6.2 Land use estimates for fulfilling the demand of biomass for biomaterials

Compared to the demand for energy, the demand for biomass for organic chemical production is much more modest, as can be seen from Figure 9. Here, different options for fulfilling this demand in terms of land use of different biomass feedstock types are addressed by rough estimates (see assumptions and calculation in Appendix 2).

The total consumption of fossil based bulk chemicals was in the order of 360 million ton in 2010 (UNEP 2013). Replacing this amount of fossil based chemicals with biobased ones would require in the magnitude of 70-140 Mha agricultural land for feedstock production, if using starch from sugarcane (lower land use) and corn (higher land use), respectively. These amounts of land use correspond to approximately 5-10%, of the current global agricultural land. If using 2G energy crops instead, it would require around 50-90 Mha agricultural land, corresponding to approximately 3-6% of the current global agricultural land. If instead using degraded land (or low productivity marginal land) for the energy crops, the area needed would be in the range of 90-900 Mha, depending on the degradation level of this land. This would correspond to between ~20% and ~200% of the available degraded land.

For comparison Dornburg et al. (2008) estimate a land use of 126 Mha and 52 Mha, respectively, for substitution of 300 million ton petrochemicals with biobased ones, using starch and lignocellulosic feedstocks (on agricultural land). Extrapolating these results to substitution of 360 million ton petrochemicals (2010 production) yields approximately 150 and 60 Mha for starch and lignocellulosic feedstocks, respectively. This fits rather well with results obtained here, considering the major uncertainties and crude assumptions.

In 2050 the demand for organic chemicals is projected to increase to roughly 1.2 billion ton. If assuming that by 2050 most organic chemicals can be produced from 2G biomass, then producing all organic chemicals on degraded land would require 300-3000 Mha. This corresponds to between ~60 and ~600% of the globally available degraded land. Using only degraded land can thus cover a substantial part of the global need for organic chemicals, but may not be enough to fulfill the demand. Using agricultural residues, e.g. from food production, as well as other biomass residues, could decrease the land need.

6.3 Biomaterials and impact on food security

The concern for impact on food security from using biomass for biofuel production has long been a debated topic. And while the demand for biomass for biomaterials is much smaller than the potential demand for biomass for biofuels, some of the same discussions may transfer to biomaterials. Thus it seems relevant to shortly address some of the key issues in the debate, which are of potential relevance for biomaterials.

It is argued by some that biofuel production, with the focus on 1G, competes with global food production and may lead to increased hunger in third world countries. The picture is however much more diverse than that. Two main points are discussed in this context; competition for land and food price impacts.

For the land competition aspect, it is true that 1G biomass feedstock production for biofuels, and biomaterials, use agricultural land, which could otherwise have been used for food production. This is however not the same as the production of biofuels and biomaterials leading to hunger, as long as enough land (with the right geographical distribution) is left for food production. In fact, the global crop production in 2010 was enough to feed 12 billion people, and even more can be produced (Hamelinck 2013). Thus while there may not be enough biomass to feed the entire world demand for both food, feed, energy and materials, there should be room for substantial biomass utilization for biobased products before actually competing with needed food production. Instead, local hunger issues primarily arise due to bad harvests, low agricultural yields, problems with transport and proper storage of the food, food waste and conflicts (Hamelinck 2013).

If growing 2G biomass on agricultural land, this competes for land in the same way as 1G, and the determining factor for the better feedstock crop should be determined in terms of yields (Carus and Dammer 2013). However 2G biomass feedstock is often able to grow on degraded or marginal land not suited for agricultural production, in which case there is no competition.

For the issue of rising food prices, European biofuel and biodiesel demands are considered to have increased world grain prices with ~1-2%, and oilseed prices with ~4% up to 2010, and may affect them further due to future demands (Hamelinck 2013). These direct impacts on food prices arise when using 1G biomass feedstock. However, other factors such as food storage and transportation issues, food waste and financial speculations have much more impact on local food prices (Hamelinck 2013). Another aspect of the food price discussion is that earlier, the issue of dumping food prices has been much debated as threatening the food security and leading to local producers not being able to sell their products (Hamelinck 2013). Thus, in case of increasing food prices, it becomes harder for local customers to afford food, whereas it increases the income of e.g. local farmers, and vice versa, and both may have an impact on food security, making the issue a lot more complex.

Another suggested food security aspect of growing 1G biomass as industrial feedstock for biofuels and biomaterials is that this biomass can also be seen as a potential ‘food buffer’ that could be allocated to cover food demands in case of a food crisis (Carus and Dammer 2013).

A final aspect worth noting concerning the issue of food availability is the consumption patterns. Today, the largest amount of biomass use by far (e.g. nova-Institute 2013) goes to feed. Thus, part of the discussion of how much land is needed for food production also depends on the future diet of the global population, and there is a large potential for biomass savings if primarily fulfilling the global food demand with crop-based food products, compared to a more meat rich diet.

7 Environmental performance of biomaterials

7.1 LCA results of biomaterials compared to fossil counterparts

The aim of this chapter is to provide a review of the current state-of-the-art within environmental impact results from LCAs on biomaterials compared to fossil based counterparts.

Conclusions on the relative environmental sustainability of biobased products compared with their fossil based counterparts cover a wide range. However, some general conclusions from LCA studies on biomaterials are:

- Biomaterials generally perform better than their petrochemical counterparts with respect to fossil fuel consumption and climate change impacts (Weiss et al. 2012; Tufvesson 2010, Weiss et al. 2007; Patel et al. 2005). However, this may change if the feedstock is planted on previously high carbon stock land (Kim et al. 2009) or when including GHG emissions from ILUC, which may be substantial (e.g. Weiss et al. 2012).
- Biomaterials often have a higher impact than conventional products in the case of eutrophication and stratospheric ozone depletion (e.g. Weiss et al. 2012; Weiss et al. 2007).
- For acidification, some conclude that biomaterials generally have a higher impact than conventional products (e.g. Tabone 2010; Tufvesson 2010; Weiss et al. 2007), but others group it with the rest of the impact categories with inconclusive results, indicating that the results vary between different types of biomaterials (Weiss et al. 2012).

Also, biomass feedstock production use land and thus include a number of LULUC related impacts, which are however in many cases not consistently included in LCA, as mentioned in Chapter 1, and addressed more specifically in Chapter 5 (selected impacts).

While there are trends in the general LCA conclusions outlined above, it is also clear that no overarching generally applicable conclusion can be drawn on the environmental performance of biomaterials compared to their petrochemical counterparts. This underlines the importance of including all relevant impact categories, in order to identify and avoid problem shifting. It also highlights that environmental performance of biomaterials relative to fossil counterparts is case specific, emphasizing the need for LCAs on case level.

Further, the above conclusions on environmental performance of biomaterials may improve if using 2G biomass feedstock rather than 1G, as 2G biomass feedstock is generally expected to have a better environmental performance than 1G (e.g. Cherubini and Jungmeier 2010). Compared to 1G biomass, 2G biomass e.g. generally has a lower need for agricultural input such as fertilizer, pesticides and irrigation (e.g. Dohleman et al. 2010)) and has higher soil organic carbon (SOC) sequestration potentials (e.g. Anderson-Teixeira 2009) and can reduce erosion (e.g. Somerville et al. 2010). Bioproducts based on 2G biomass can thus increase savings in GHG emissions and non-renewable energy use when substituting fossil products, compared to 1G (e.g. Dornburg et al. 2008) and has the potential to decrease the impact on water quality and water use (e.g. Gnansounou 2010). Further, it can decrease the land use and especially the use of agricultural land, as discussed in Chapter 6.2. If using 2G feedstock in the form of biomass residues and waste, no land use is required and many additional agricultural inputs can be completely avoided. However, the use of residues may induce other impacts, such as decrease in SOC, depending on the degree of removal of residues, as well as other management issues etc. (e.g. Cowie et al. 2006).

In terms of bioproducts[4] based on algae biomass, there may also be interesting perspectives. Some promising features of algae biomass as feedstock for bioproducts are that they can save use of land, there is a wide availability, and CO_2 capture and biomass yields are high (e.g. Posten and Schaub 2009; Clarens et al. 2010). However, algae feedstock may still have higher impacts in most environmental impact categories compared to conventional crops, including fossil energy use and GHG emissions (Clarens et al. 2010) and improvements are needed in order to make algae as feedstock for biobased production a sustainable and commercial viable reality (e.g. Sander and Murthy 2010).

The non-uniformity of biomaterials and their environmental performance due to different pathway options is addressed in the following subchapters.

7.2 Pathways of biomaterial product life cycles

Consideration of the potential pathway diversity of biomaterial based products is addressed here. A conceptual illustration of this diversity is given in Figure 10, and the potential differentiation options with inherent environmental impacts for the different life cycle step options is discussed in the following subchapters.

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[4] Assessments generally consider biofuels such as biodiesel, however in terms of feedstock use this can also be used to give an indication for biomaterials

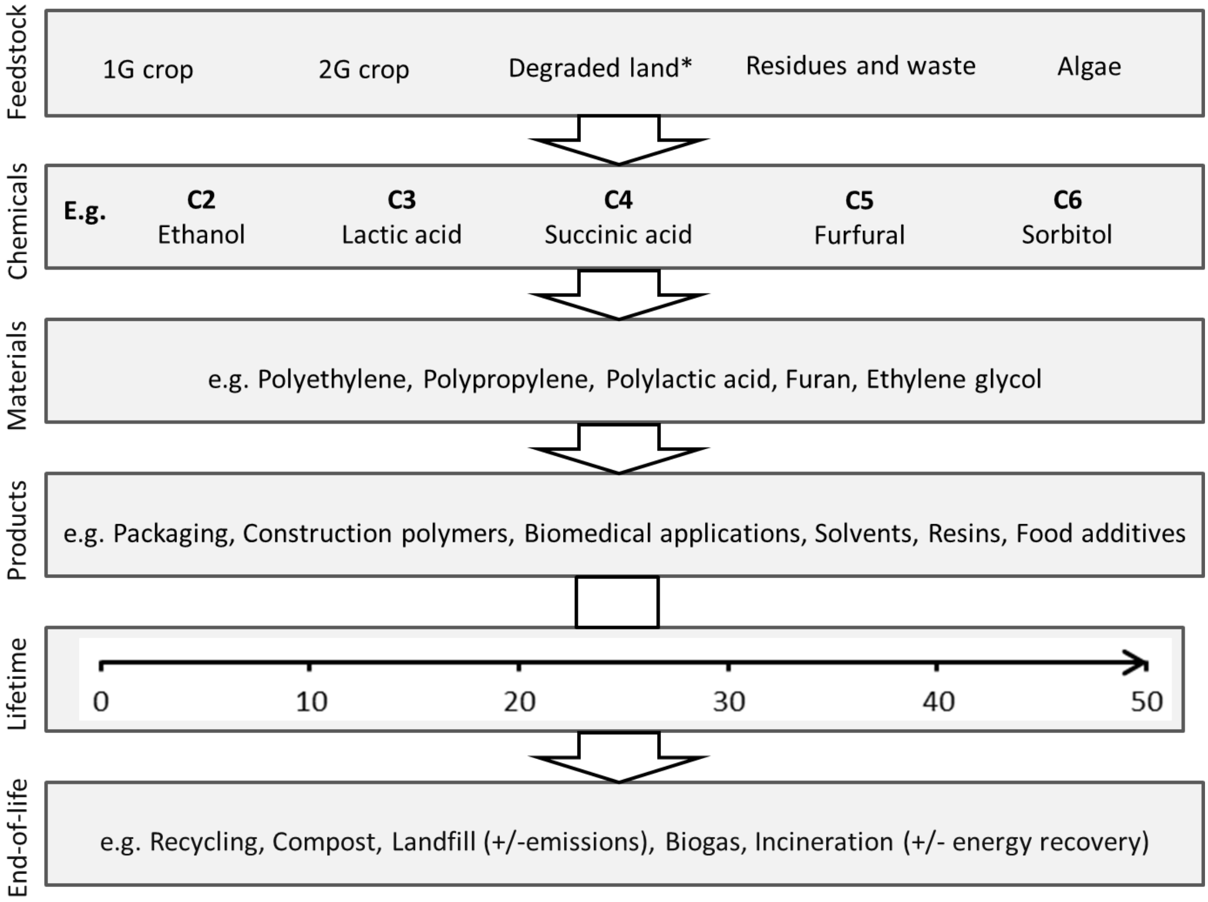

Fig. 10 Conceptual illustration of potential pathways for biomaterial product lifecycles. Each of the vertical arrows cover different possibilities for production routes and/or transport systems, distances etc. *While degraded land is not in itself a feedstock, there is an option for 2G feedstock production on degraded or marginal productivity land, which is important to include due to different potentials/impacts compared to production on more fertile land. Examples on potential biobased chemicals and materials are based on Cherubini and Strømman (2011) and Carus et al. (2013)

7.3 Biomass feedstock type and production

Some of the main issues impacting environmental sustainability of the biomass feedstock are:

- Former land use
- Type of biomass
- Management practice
- Climate and soil conditions

Former land use and type of biomass feedstock

Biomass feedstock production for biomaterials requires use of land and; how much depends on the potential yield of the biomass. For instance, the land need for biomass production if using sugarcane starch as feedstock is almost half of that needed if using corn starch (de Vries et al. 2010), while using energy crops such as miscanthus and switchgrass has the potential to reduce the land need even further (e.g. Sanderson 2006) (see yield and land use estimates of those feedstocks in Appendix 2).

Besides the quantity aspect of land use, the quality in terms of environmental impacts is also dependent on the type of biomass feedstock produced, as well as on the former land use. Generally, converting natural forests and other land types rich in biodiversity and biogenic carbon to crop production will have larger impact on biodiversity loss and atmospheric CO_2 emissions than using other land types; if using degraded land for establishing bioenergy plantations this will on the contrary increase biogenic carbon stocks, improve soil quality and positively impact the quality of aquatic ecosystems (e.g. Lal 2005). For the overall global warming change following a LUC from one type of land use to another, albedo change impacts may also be highly important, but often with opposite operational sign than impacts from biogenic carbon fluxes. E.g. the clearing of a forest will lead to global warming impacts from oxidation of the biogenic carbon stock, but this may in some cases be more than counterbalanced by the climate cooling induced by the entailed change in surface albedo (Randerson et al. 2006; Bala et al. 2007; Betts 2007; Davin et al. 2007; Cherubini et al. 2012a; O'Halloran et al. 2012) as also discussed in Chapter 5. (See Chapter 5 and Article 4: Jørgensen et al. (2014) for further discussion on potential impacts and tradeoffs from biogenic carbon flux, albedo and biodiversity changes from different former land uses to a biomass crop production, based on a hypothetic case study). (For general differences in environmental impacts between 1G, 2G and 3G, see Chapter 7.1).

Management practice

While some agricultural input requirement is determined by the crop type, different management practices can be employed. Differences can e.g. include whether, and to which degree, tilling, fertilizers, pesticides and irrigation are employed in the crop production. Changes in management practices can substantially change impacts on e.g. SOC (Cowie et al. 2006) and eutrophication and stratospheric ozone depletion (Weiss et al. 2012). However change in management practice for reducing environmental impacts of the production will often also impact yields, and thus may lead to increased demand for land, which need to be taken into consideration in the overall assessment of the environmental performance (e.g. Weiss et al. 2012).

Climate and soil conditions

The climate and soil conditions of an area used for crop production can have high impact in terms of potential biomass yield (e.g. McKendry 2002) and SOC content (Mishra et al. 2012, Cowie et al. 2006). It will also influence global warming impact potentials; both through the influence on biogenic carbon stock, and through surface albedo, which is affected by climate aspects such as seasonal snow cover (e.g. Claussen et al. 2001). Climate conditions also impact the need for irrigation to obtain optimal crop yields (e.g. Mishra et al. 2012).

7.4 Conversion route and product type

- Conversion route
- Intermediate chemicals
- End products
- Transportation

Conversion route and intermediate chemicals

There are several conversion steps involved in the production of biomaterial based products. First there is the conversion of the biomass feedstock through a number of processes to bulk chemicals. In some cases, the bulk chemicals may also be the end product. But those chemicals can also be building blocks for a number of other chemicals and materials (e.g. UNEP 2013, Cherubini and Strømman 2011). The environmental performance of the end product thus depends on the performance of all conversion processes taking place in the production, potentially via a number of intermediate chemicals. The same biobased end products can often originate through different conversion routes, which all have influence on the environmental performance. Conversion technologies from biomass to chemicals include e.g. enzymatic, thermal and chemical processes. The influence of the conversion route on the environmental profile of the end product depends e.g. on efficiency, both in terms of use of the biomass feedstock, but also in terms of additional inputs such as energy, chemicals and water.

End products

The type of end product is determining not only for the amount of biomass feedstock needed and associated environmental impacts, but also for the duration of temporary carbon storage in the product. This duration is the time from atmospheric CO_2 sequestration in biomass[5] until the final re-emission of the carbon to the atmosphere after the disposal of the product, and is thus dependent on the lifetime of the product (and potentially on the end-of-life handling which is addressed in Chapter 7.5). The climate change mitigation value or impact of the temporary carbon storage in biomaterials is highly dependent on the time of sequestration and duration of the storage (see Chapter 3.5 and Article 3: Jørgensen et al. 2015).

Transportation

The issue of transportation is involved several times during the product life cycle; both of biomass from field to conversion facility (which may include transport to several intermediate production facilities) before the end product is transported to the consumer. Finally there will be some degree of transportation from the consumer to the final disposal. Environmental impacts from

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[5] If the biomass has been produced for the purpose of producing the biobased product, and the stored carbon thus can be assigned to this, as it would not have been stored otherwise. This is not the case if e.g. using biomass from virgin land etc. where the carbon was already stored, and the carbon storage can thus not be assigned to the biomaterial production.

transportation depend on distance, transport mean, infrastructure, fuel type etc., and may have substantial influence on the environmental profile of e.g. end products with low density (e.g. Patel et al. 2005).

7.5 End-of-life handling

- Geographic location
- Waste management options
- Potential prolonging of carbon storage

Geographic location
For the end-of-life handling, geographic location is a key parameter, due to national differences in waste management infrastructure (e.g. Patel et al. 2005).

Waste management options
Waste management options for biomaterials cover a wide range including recycling, incineration, composting and landfilling (e.g. Weiss et al. 2012; Patel et al 2005). The type of waste management applied may have substantial influence on the life cycle GHG impacts of biomaterials. E.g. GHG variations from different waste treatment scenarios of a specific biobased product have been shown to be as large as the difference in GHG impacts between the biobased product and its fossil fuel reference product (Würdinger et al. 2002).

Potential prolonging of carbon storage
In the case of landfilling biomaterials, this may enhance the duration of the temporary storage of the carbon bound in the biomaterial, to the extent that the biomaterial is not degraded under the given conditions in the landfill. The potential climate change mitigation benefit from prolonging the temporary carbon storage should be seen in comparison to the environmental impact savings from alternative waste management options, e.g. fossil fuel replacement in case of incineration with energy recovery, or reduced materials production in case of recycling.

8 Environmental perspectives of biomaterials

While Chapter 7 addresses the environmental performance of biomaterials, this chapter addresses the environmental perspectives of biomaterials, that is, adding a future perspective. Both in terms of potential competition and synergy effects of biobased products, and in terms of future potential development in environmental performance of biomaterials relative to that of conventional fossil fuel alternatives.

8.1 Competition and synergy issues

As discussed in Chapter 6, the amount of sustainably available biomass in the future is not likely to cover the total demand of a biobased society, replacing all fossil based materials and energy. Thus, the biomass that will be available for the biobased society vision should be prioritized to the use where it has most value.

Competitiveness of biomaterials compared to biomass use for energy purposes

When comparing the environmental performance of biomaterials to that of bioenergy, several studies conclude that biomaterials currently come out more favorable in terms of potential for saving energy and reducing GHG emissions (Patel et al. 2005). The temporary storage of carbon in biomaterials may also pose an environmental preference of biomaterials compared to biofuels (Carus and Dammer 2013), depending on timing of carbon sequestration and duration of the storage (Article 3: Jørgensen et al. 2015). Besides, biomaterials are more high-value products and seem to have a better economic performance than bioenergy, while also having the potential to create more jobs (Carus and Dammer 2013). Moreover, biomaterials cannot easily be replaced by other renewables, which is not the case for bioenergy (Carus and Dammer 2013).

As the involved technologies are in many cases still rather new with potentials for improvements, these results are preliminary and are subject to change depending on future innovations. Another aspect is to which degree the use of biomass for materials and energy is competition and to which these may be produced in synergy as complementary products (Patel et al. 2005).

Integrated Biorefineries and carbon cascading

Complementary production of e.g. biomaterials and biofuels is suggested to be done through integrated biorefineries. The general concept of a biorefinery is a biobased equivalent to the normal petrochemical refineries existing today, producing fuels and other products in an integrated process. While the borefinery concept already exist to some extend today, the technology is still on a preliminary level and significant development in this field is expected in the coming years (Weiss et al. 2012). Utilizing biomass for producing energy and materials in integrated biorefineries through the use of a range of technical processes is expected to optimize the energy and material recovery of the available biomass (Cherubini and Jungmeier 2010).

Another suggestion for optimizing the use of the available biomass resources is the concept of ‘carbon cascading’, which means that the biomass is first used for biomaterial products, and at their end-of-life they are used for producing bioenergy, through incineration with energy recovery (e.g. Weiss et al. 2012).

8.2 Maturity of competing technologies

An important perspective of environmental performance of biomaterials relative to conventional fossil counterparts is the aspect of the age of the competing technologies. While the petrochemical industry is based on a mature technology which has been optimized for many years, the same is not the case for many of the biotechnologies used for producing biomaterials (e.g. Weiss et al. 2007). Thus, substantial improvement potentials of biotechnology are expected in terms of both efficiency optimization and in terms of the integrated production of biofuels and biomaterials in biorefineries (Patel et al. 2005).

8.3 Future feedstocks

Future biomass feedstocks

While most biomaterials being produced today are based on 1G biomass feedstock, the development in use of advanced biomass feedstock has a major focus today. As outlined in Chapter 7.1, the environmental performance is likely to improve on a number of impacts if using 2G rather than 1G biomass feedstock. According to this, biomaterial products have a promising potential for future environmental improvement relative to conventional fossil based products through increased use of 2G feedstock.

Future fossil fuel feedstock

The biomass feedstock is not the only feedstock which may change in the future. With oil resources going fast towards depletion, accompanied by rising oil prices, new types of fossil fuel feedstock for different products are getting increased attention. Two such options are shale gas and oil tar sands. Some environmental aspects of those fossil feedstock types are that both have a life cycle water consumption which is about twice as high as for conventional oil (King and Webber 2008) and both lead to changes in quality and availability of land (Jordaan 2012). Further, the use of oil tar sands at the moment leads to approximately a three times higher GHG emission impact than conventional oil (NETL 2008; Charpentier et al. 2009). Thus if using shale gas and oil tar sands as fossil material feedstock in the future, increases in environmental impacts compared to using conventional oil as feedstock needs to be considered, thus improving the relative environmental performance of biomaterials compared to fossil materials.

9 Conclusion

This chapter summarizes main conclusions from the PhD project presented in this dissertation

9.1 The CTP approach for GHG emission and temporary carbon storage assessment

With quickly approaching climate tipping points, which are expected to lead to dramatic and potentially irreversible changes if crossed, there is a need for addressing the urgency of mitigating climate change in order to stay below such levels. This is not included in the GWP. The suggested CTP approach covers this need, by expressing GHG emission impacts divided by the ‘capacity’ of the atmosphere for absorbing the impact, without exceeding the target level. The CTP is suggested to compliment the GWP, which should still be used to represent the long-term climate change impacts of GHG emissions.

Further, the potential climate change mitigation value of temporary carbon storage, in terms of contributing to avoid or postpone the crossing of climate tipping points, can be included in the environmental profile of biomaterials through the use of an adapted version of the CTP approach. The CTP mitigation value of temporary carbon storage is very dependent on the timing of sequestration and re-emission of carbon relative to the target time and the duration of the storage. It may even lead to an increase in CTP impact if the carbon is re-emitted before the expected time of crossing the target level, while for storage beyond this time, mitigation values increase the further the storage goes beyond the target level. Implementation of the CTP approach in LCA for both emissions and temporary carbon storage is supported by the CTP characterization factors provided for several GHG concentration development scenarios and a target level of 450 ppm CO_2e.

9.2 Potential importance of (temporary) carbon storage in biomaterials

The climate change mitigation value of temporary carbon storage lies in temporarily removing CO_2 from the atmosphere, if this can contribute to either bridging, or at least postponing for a noteworthy period, the crossing of a climatic target level, which is otherwise expected to induce dangerous climate change impacts. Long-term carbon storage in biomaterials has the potential to provide substantial contribution to avoid or postpone (depending on the general development in atmospheric GHG concentration) the crossing of the expected dangerous climate change level of 450 ppm CO_2e. The total magnitude of this potential is dependent on the market share biomaterials will gain in the future.

While single product carbon storage may be temporary, the resulting stock changes are usually more long-term, or even permanent. Substitution of petrochemical materials with biomaterials (and even more so a shift from a fossil based to a biobased society) would lead to reduction of carbon fluxes from fossil fuel reservoirs to the atmosphere, as well as increase carbon fluxes from the atmosphere to the anthroposhere (via the biosphere) and potentially also increase the carbon stock in the biosphere. These carbon flux changes lead to a reduction in the atmospheric GHG concentration level, which will be permanent as long as the biomaterial production is continued at the same level or is increased.

9.3 Potential influence and tradeoffs of selected current non-standard LCA impacts

Changes in biodiversity, surface albedo and total biogenic carbon flux (including SOC) following a LUC are often not included in LCAs of biomaterials. However, all three types of impacts are potentially of great importance. Further, potential tradeoffs exist between some of those impacts. Thus it is important to include the best possible assessment of these impacts in LCA of biomaterials, in order to get a realistic picture of the overall impacts from a biomass feedstock crop establishment, and thus downstream products. However, for assessment of several of those impacts, challenges exist in terms of e.g. the requirements to availability of local data as well as the preliminary state of some methods.

9.4 Environmental performance and perspectives of biomaterials

Generally, biomaterials are in LCA studies found to save fossil fuel consumption and reduce global warming compared to conventional petrochemical materials. At the same time, biomaterials often increase other impacts such as eutrophication and acidification, while also carrying a land use and related environmental impacts. Many of those aspects are expected to be improved if using 2G biomass feedstock for biomaterials, rather than 1G. However, no general conclusion on the overall environmental performance of biomaterials relative to petrochemical materials can be made, as biomaterials are very diverse in terms of both end products and life cycles.

Future perspectives of biomaterials include the option for optimization of biomass use through integrated co-production of biomaterials and biofuels in biorefineries, as well as the expectations of efficiency improvements of technologies for biomaterial production, relative to the efficiency of the more mature technology for petrochemical material production. Finally, the aspect of future potential shifts in feedstocks, both in terms of the option of using biomass beyond 1G as feedstock for biomaterials, and the potential use of new fossil fuel feedstocks, may change the relative environmental performance of biomaterials and conventional petrochemical materials.

In terms of potential for biomass feedstock availability, it is estimated that there will be enough biomass feedstock available for future biomaterial production without competing with food for the land, even if the entire global need for organic chemicals (including polymers) is based on biomass in the future. However, as there is not likely to be enough biomass available to cover both the entire future demand for energy and materials, some degree of competition between these two uses is expected. Current estimates point to biomaterials being both more valuable and yielding higher environmental savings than bioenergy, giving the former a competitive advantage.

10 Recommendations for future work

Through the work during this PhD project, potentials for further elaboration and application of methods beyond the scope of this project have been identified and recommendations for future research are briefly outlined in this chapter.

10.1 Calculation of additional CTP characterization factors

The developed CTP approach has been applied to a number of atmospheric GHG concentration development scenarios, calculating characterization factors for at target level of 450 ppm CO_2e for the three major anthropogenic GHGs, CO_2, CH_4 and N_2O, with emission times from present until the respective target times. For emissions of those GHGs, CTP characterization factors have been calculated for all four representative concentration pathway scenarios (RCPs), given by Meinshausen et al. (2011), which are also used for the 5th IPCC report (Stocker et al. 2013). CTP characterization factors for temporary carbon storage have been calculated for two of the RCPs as described in Chapter 3.5, with time of carbon sequestration from present until the respective target times, for storage durations of 2 to 50 years.

Further work should be done in terms of calculating CTP characterization factors for other GHG emission types (e.g. CFC, HCFC and HFC gasses), for the four RCP scenarios. This is possible to do directly by applying the proposed CTP method (see Article 2: Jørgensen et al. 2014) if the atmospheric lifetime and specific radiative forcing of those GHGs are available. Further, characterization factors for other climatic target levels and other GHG development scenarios can be calculated, depending on which climatic target level is pursued and which atmospheric GHG concentration development pathway is expected. Likewise, CTP characterization factors of temporary carbon storage for the two last RCP scenarios (RCP 4.5 and RCP 8.5) should be calculated as well, which can be done by using the developed method for this special aspect (see Article 3: Jørgensen et al. 2015).

10.2 Application of the CTP approach for non-GHG climate forcings

Besides calculating CTP factors for all relevant GHGs, another important aspect is the inclusion of other important non-GHG drivers of climate forcings, such as change in surface albedo. The application of the CTP approach to such aspects can be done by expressing their impacts as CO_2e, in terms of effective forcing change impact, from the time the change in climate forcing begins until the target time. The formulation of this requires further elaboration and is an issue for further work.

10.3 Application of the CTP approach in a Planetary Boundary context

As the remaining atmospheric capacity for receiving GHG emissions up to the point where the target level is reached is treated as a limited ‘resource’, the nature of the CTP approach is in line with the idea of defining absolute limits to environmental impacts in terms of ‘planetary boundaries’ (Rockström et al. 2009), as mentioned in Article 2: Jørgensen et al. (2014). The CTP is thus based on a planetary boundary for climate change, striving to avoid the crossing of dangerous climate tipping points. The approach developed for the CTP could also be applied to other impact categories, provided that boundaries/target levels can first be established, quantifying the associated remaining capacities and thus the impact factors. Further work should be done in terms of pursuing the potential of the capacity concept of the CTP approach to establish ‘boundary exceeding potentials’ in other impact categories.

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12 Appendix 1: Global biomass potential, and demands from materials and energy

This appendix gives an overview of available biomass potential, as well as biomass demand, now and in the near future, based on a review of literature estimates. Some key assumptions are included; for more on specific background assumptions, refer to references. There may be references using data from same original source. Newest references from left hand side of figures.

Note: Original data have generally been given by references as energy potentials and demands (except for biomass demand for biomaterials); thus data have been converted to mass units (dry weight) by using an energy density range for the biomass of 15-19 EJ/Gt [6]

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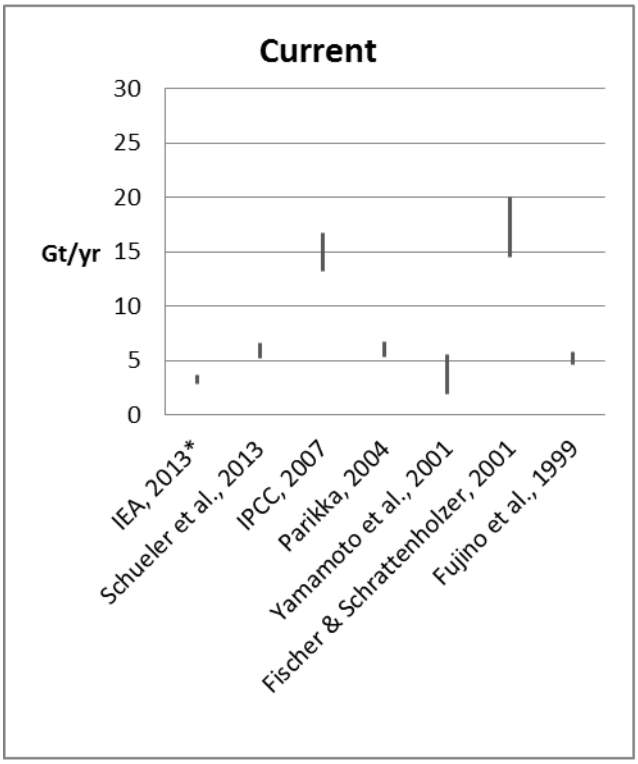
[6] The range of energy content of 15-19 GJ/ton biomass (dry weight) is used, as almost all biomass feedstocks destined for combustion are in this range, including agricultural residues, which are mainly within the range of ~15-17 GJ/ton, and most woody materials, which are within the range of 18-19 GJ/ton (US DOE 2012). Also energy content of 1G biomass feedstock such as corn and sugar cane is within the range of ~15-19 GJ/ton (see e.g. ECN 2013) and the energy content of energy crops is ~19 GJ/ton (Hoogwijk et al. 2003; van Sark et al. 2006).

12.1 Global biomass potential



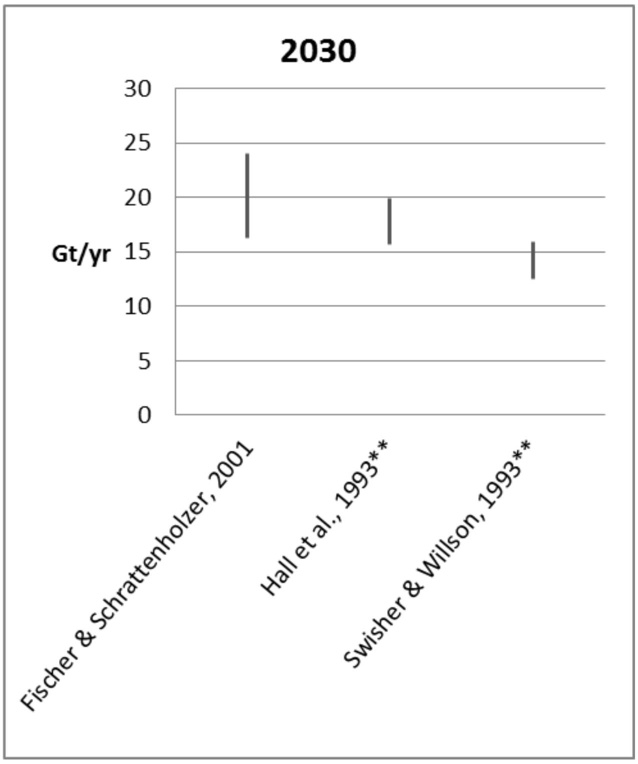


Fig. A1.1 Current global biomass potential. Note that ‘current’ is an approximate label here, as references are of different age, and often the data used are some years older. For Fischer and Shcrattenholzer (2001) estimates are for year 2015 (read off from Fig. 2 in the study). For the case of Yamamoto et al. (2001) the range illustrates the span from the total potential (upper end of range) to the practical potential (lower end of range) (read off values from Fig. 17 in the study). *The value for IEA (2013) is the present (2012) energy utilization from biofuels and waste

Fig. A1.2 Global projected biomass potential in 2030. For Fischer and Shcrattenholzer (2001) estimates are read off from Fig. 2 in the study as no exact numbers were available. **Estimates from these references have been quoted from Jensen and Thyø (2007); estimates for Hall et al. (1993) have been grouped with studies assessing the bioenergy potentials in 2025-2030 in Jensen and Thyø (2007) (based on Berndes et al. (2003) stating the temporal scope to be 2025-2050); estimates for Swisher and Willson (1993) have been converted to primary potential 2030 in Jensen and Thyø (2007)

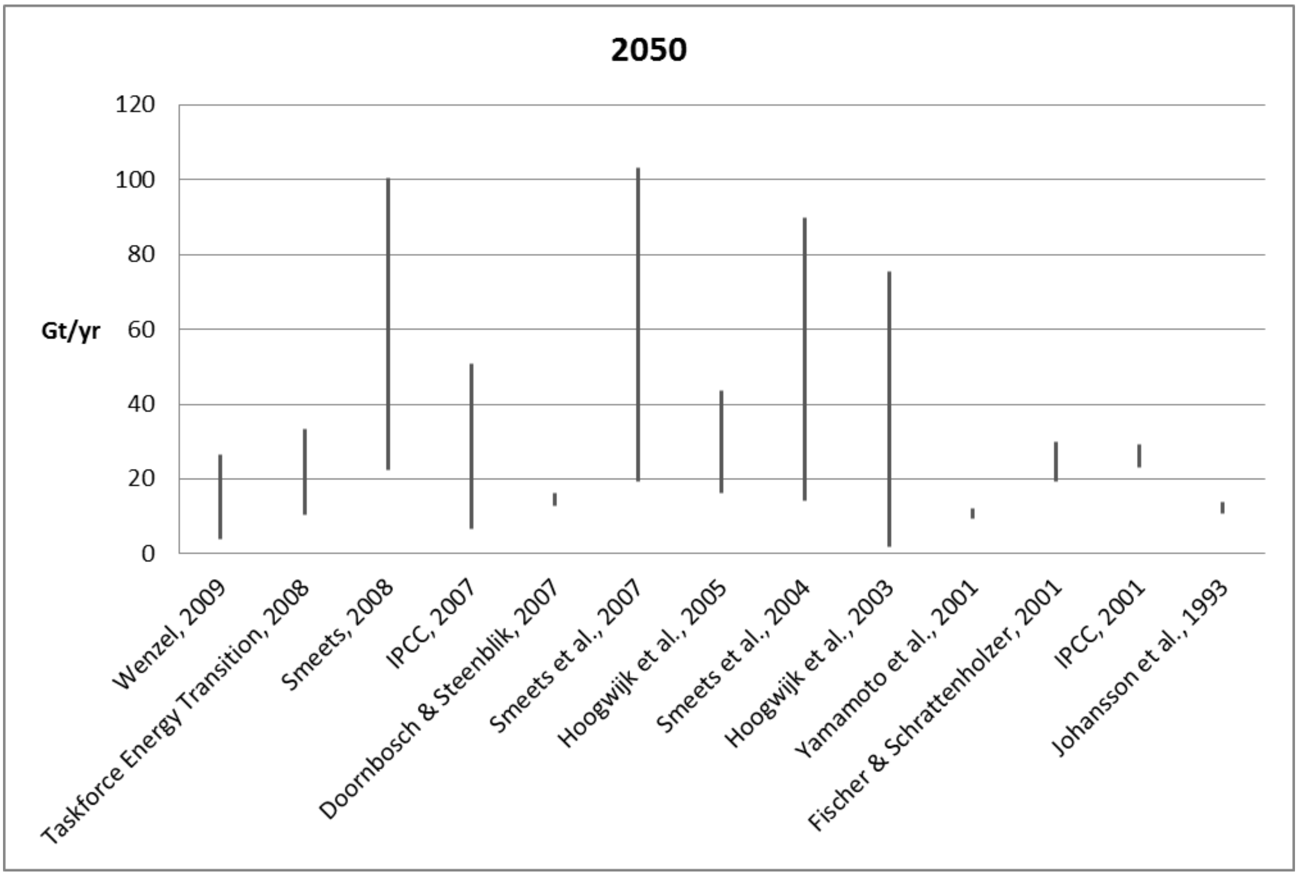


Fig. A1.3 Global projected biomass potential in 2050. In the case of Wenzel et al. (2009) the range illustrates the biophysical biomass potential, with the lower end including economic and market considerations in availability

12.2 Global biomass demand

Global biomass demands listed here are for full substitution of fossil fuel feedstock consumption by biomass feedstock, both for energy and organic chemicals.

For energy

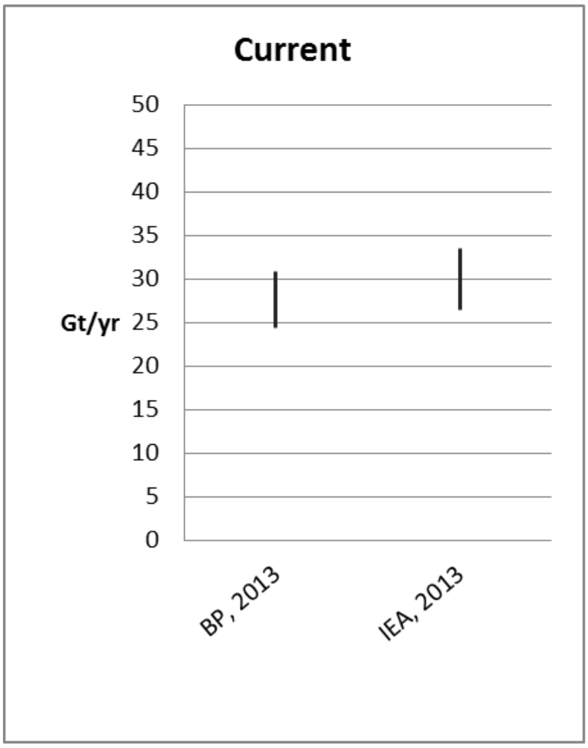


Fig. A1.4 Current global biomass demand for energy. Given as primary energy consumption in 2012 (BP 2013) and 2011 (IEA 2013)

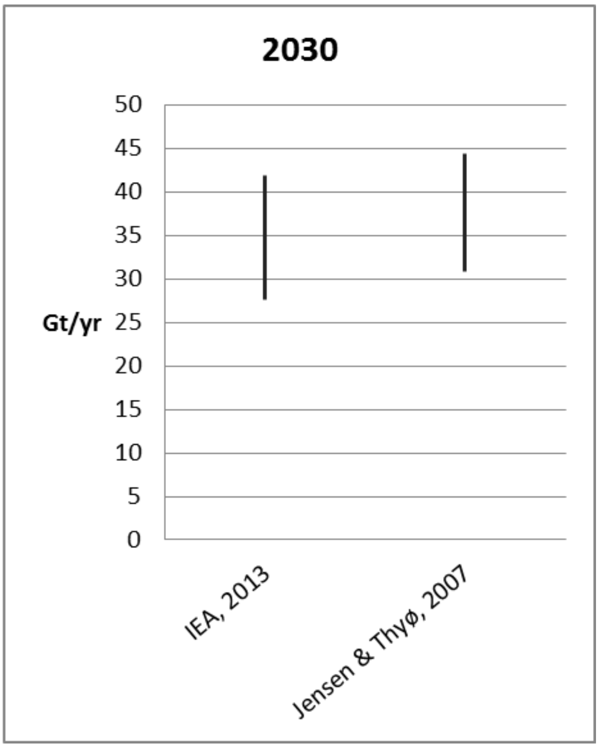


Fig. A1.5 Global projected biomass demand for energy in 2030. Both estimate ranges covers different scenarios. In the case of IEA (2013) values are read off from figure in the study (p. 46, top)

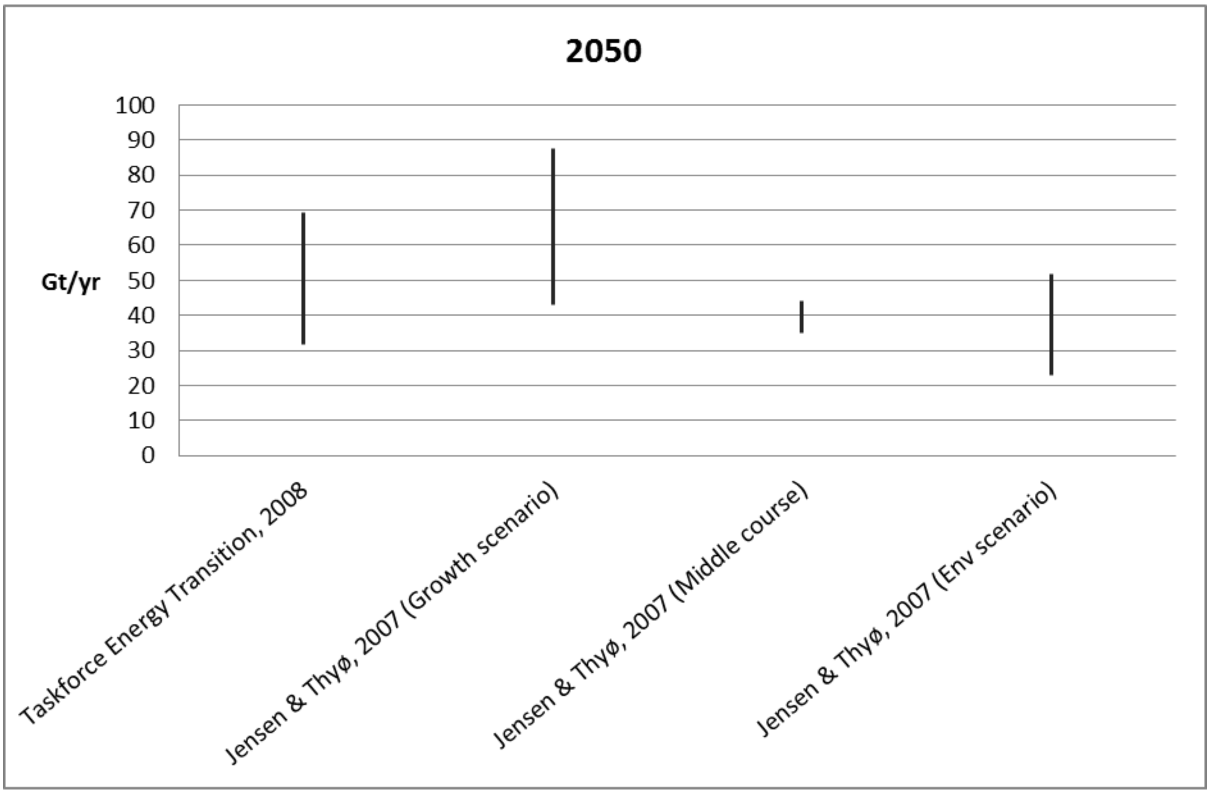


Fig. A1.6 Global projected biomass demand for energy in 2050. The ranges from Jensen and Thyø (2007) cover estimates from different scenarios; an environmental oriented future, a middle course future scenario and a high economic growth future

Note: Energy demand estimates exclude energy demand covered by nuclear power, as well as hydro power and other renewable energy sources other than biomass and waste (to the extent that the latter have been separable in the reference), meaning that it gives the global biomass demand for substituting fossil fuel energy production. (Except for the estimate from Taskforce Energy Transition (2008) which gives the total global energy demand in 2050; however this estimate range lies within the ranges of estimates from Jensen and Thyø (2007) and thus does not affect neither upper nor lower energy demand in the summary in Figure 9 in the dissertation.

For organic chemicals

Some of the estimates used here are approximated from original values given by the references, and are thus not given directly by the references (as outlined in notes below).

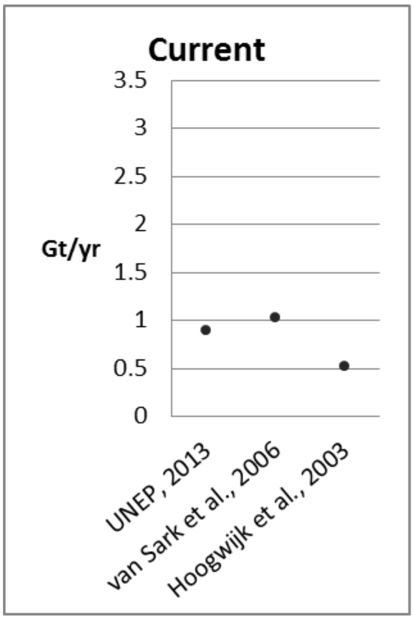


Fig. A1.7 Current (year 2010) global biomass demand for organic chemicals. Estimates based on van Sark et al. (2006) and Hoogwijk et al. (2003) are averages of original values for year ~2000 and 2020

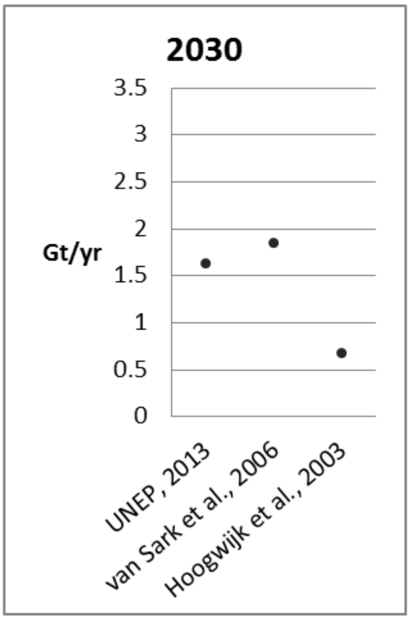


Fig. A1.8 Global projected biomass demand for organic chemicals in 2030. The estimate based on Hoogwijk et al. (2003) has been extrapolated from the 2020 value using a 2% annual increase as assumed by this reference

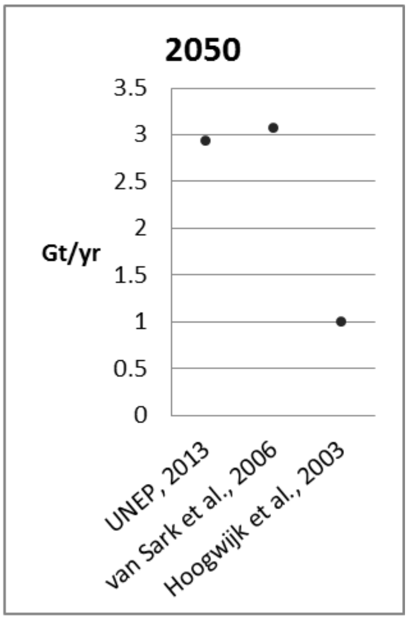


Fig. A1.9 Global projected biomass demand for organic chemicals in 2050

Note: Values given by Hoogwijk et al. (2003), are given as the demand of biomass for substitution of petrochemicals, and results from a conversion efficiency of 40% (2.5 ton biomass/ton product), as dictated in the reference. Estimates from van Sark et al. (2006) give the demands for polymers; these have been extrapolated to cover organic chemical demands, using that polymers are stated in the reference to cover ~2/3 of organic chemicals (excluding solvents and surfactants). These estimates have been converted to primary biomass demand by applying a conversion efficiency of 40%, as found in Hoogwijk et al. (2003). Values from UNEP (2013) cover global production in year 2010 of the 7 top bulk chemicals (which is feedstock for many thousands downstream chemical products): Methanol, ethylene, propylene, butadiene, xylenes, benzene, toluene (ethanol not included here; it is mainly used as fuel). Future demands have been projected from current level assuming a 3% global growth per year for organic chemicals until 2050, which is the approximate increase for global chemical sales for the period expected in the reference. Values have been converted to primary biomass demands by applying the conversion efficiency of 40%, as found in Hoogwijk et al. (2003).

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13 Appendix 2: Land demand for a biobased global organic chemical production

Table A2.1: Current global organic chemical production (2010)

Production [Mt]	Land need using different feedstock crops[a] [Mha]			
			Energy crops	
	Corn starch[c]	Sugarcane starch[c]	Agricultural land	Degraded land
360[b]	144	74	45-90[d] 60-63[e]	90-900[f] 63-147[e]

Table A2.2: Global organic chemical production in 2050[g]

Production [Mt]	Land use for different feedstock crops[a] [Mha]			
			Energy crops	
	Corn starch[c]	Sugarcane starch[c]	Agricultural land	Degraded land
1200[h]	481	246	150-300[d] 200-208[e]	300-3000[f] 208-491[e]

[a] Rough estimates

[b] Including the 7 biggest bulk chemicals: Methanol, ethylene, propylene, butadiene, xylenes, benzene, toluene (UNEP 2013) (ethanol not included here; it is mainly used as fuel)

[c] Using ethanol as example organic chemical; yield efficiencies from de Vries et al. (2010) and an ethanol density of 0.789 t/m^3. (Using ethanol as example of organic chemicals is a very coarse assumption, both concerning conversion efficiency and carbon content of organic chemicals, but it can be used as a rough approach for obtaining an order of magnitude)

[d] Using short rotation woody energy crops on agricultural land: 10-20 t dry biomass/ha/year and a conversion factor of 2.5 t dry biomass/ton petrochemical product substituted (product not further specified) (Hoogwijk et al. 2003)

[e] Using switchgrass and miscanthus, respectively, with ethanol as example organic chemical (Sanderson 2006). Where high- and low end yields are given, high-end yields are assumed for agricultural land and low-end yields for low productivity marginal/degraded land. However, yields also depend on both the level of degradation of the land and input level of e.g. water and nutrients

[f] Using short rotation woody energy crops on degraded land: 1-10 t dry biomass/ha/year and a conversion factor of 2.5 t dry biomass/ton petrochemical product substituted (product not further specified) (Hoogwijk et al. 2003)

[g] Not considering efficiency improvement potentials

[h] Projecting from current level by assuming a 3% global growth per year for organic chemicals until 2050, which is the approximate increase expected for global chemical sales for the period (UNEP 2013)

Table A2.3: Current land use – Data including comments from Hoogwijk et al. (2003)

Land type	Size (Mha)	Comment
Global land area	13200	Recreational, human settlements and protected nature areas excl.
Inproductive land	4200	E.g. built-up, mountainous, (semi-)desserts
Agricultural land	1500	
Pasture land	3500	
Degraded land	430-580	Potentially available for energy crops

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Sanderson (2006) A field in ferment. Nature 444: 673-676

UNEP (2013) Global Chemicals Outlook – Towards Sound Management of Chemicals. United Nations Environment Program (UNEP). ISBN: 978-92-807-3320-4

14 Article collection

1. Jørgensen SV, Hauschild MZ (2013) Need for relevant timescales when crediting temporary carbon storage. Int J Life Cycle Assess 18:747-754. doi: 10.1007/s11367-012-0527-3
   The publication is available at:
   http://link.springer.com/article/10.1007%2Fs11367-012-0527-3
   This article is partly based on work conducted prior to the initiation of the PhD project

2. Jørgensen SV, Hauschild MZ, Nielsen PH (2014) Assessment of urgent impacts of greenhouse gas emissions – the Climate Tipping Potential (CTP). Int J Life Cycle Assess 19:919–930. doi: 10.1007/s11367-013-0693-y
   The publication is available at:
   http://link.springer.com/article/10.1007%2Fs11367-013-0693-y

3. Jørgensen SV, Hauschild MZ, Nielsen PH (2015) The potential contribution to climate change mitigation from temporary carbon storage in biomaterials. Int J Life Cycle Assess 20:451–462. doi: 10.1007/s11367-015-0845-3
   The publication is available at:
   http://link.springer.com/article/10.1007%2Fs11367-015-0845-3

4. Jørgensen SV, Cherubini F, Michelsen O (2014) Biogenic CO_2 fluxes, changes in surface albedo and biodiversity impacts from establishment of a miscanthus plantation. J Environ Manag 146:346-354. doi: 10.1016/j.jenvman.2014.06.033
   The publication is available at:
   http://www.sciencedirect.com/science/article/pii/S0301479714003703

   In the online version of the thesis, the articles are not included but can be obtained from electronic article databases via the links given above, or via DTU Orbit:

1. http://orbit.dtu.dk/en/publications/need-for-relevant-timescales-when-crediting-temporary-carbon-storage%28483ddcb3-7967-4b64-b109-eef22c706a38%29.html

2. http://orbit.dtu.dk/en/publications/assessment-of-urgent-impacts-of-greenhouse-gas-emissionsthe-climate-tipping-potential-ctp%2823969aff-99d0-4ab9-9006-cc2e5c7eb094%29.html

3. http://orbit.dtu.dk/en/publications/the-potential-contribution-to-climate-change-mitigation-from-temporary-carbon-storage-in-biomaterials%28a25b8417-8e05-4315-be92-2d96ec16608a%29.html

4. http://orbit.dtu.dk/en/publications/biogenic-co2-fluxes-changes-in-surface-albedo-and-biodiversity-impacts-from-establishment-of-a-miscanthus-plantation%286c101f8c-d883-4a2a-a82a-e4ad5eb88f84%29.html

This PhD dissertation addresses environmental perspectives of producing materials such as plastics that are traditionally derived from fossil resources, from biomass instead. The dissertation has a special focus on the climate effect of the temporary carbon storage taking place in biomass based materials.

In the PhD study, a method for assessing the potential value of temporary carbon storage, in terms of avoiding or postponing exceedance of critical climate change levels, has been developed. This means that this potential value of temporary carbon storage in biomass based materials can be integrated in the existing life cycle assessment (LCA) methodology and thus be taken into account in the environmental profile of biomass based materials.

Further, the importance of changes in surface albedo, biogenic carbon fluxes (including soil organic carbon) and biodiversity associated with land use and land use change for biomass production has been addressed in this PhD project.

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